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THE INFLUENCE OF ORGANICALLY MANAGED HIGH TUNNEL AND OPEN FIELD PRODUCTION SYSTEMS ON STRAWBERRY (Fragaria x ananassa) QUALITY AND YIELD, TOMATO (Solanum lycopersicum) YIELD, AND EVALUATION OF PLASTIC MULCH ALTERNATIVES

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To the Graduate Council:

I am submitting herewith a thesis written by Jeffrey Thomas Martin entitled "THE INFLUENCE OF ORGANICALLY MANAGED HIGH TUNNEL AND OPEN FIELD PRODUCTION SYSTEMS ON STRAWBERRY (Fragaria x ananassa) QUALITY AND YIELD, TOMATO (Solanum lycopersicum) YIELD, AND EVALUATION OF PLASTIC MULCH ALTERNATIVES." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

Annette L. Wszelaki, Major Professor

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THE INFLUENCE OF ORGANICALLY MANAGED HIGH TUNNEL AND OPEN FIELD PRODUCTION SYSTEMS ON STRAWBERRY (*Fragaria* x *ananassa*) QUALITY AND YIELD, TOMATO (*Solanum lycopersicum*) YIELD, AND EVALUATION OF PLASTIC MULCH ALTERNATIVES

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DEDICATION

I would like to dedicate this thesis project to my family and friends. It was a long three years but I came out alive. I am so grateful for my parents, sisters, and brother for supporting my decisions and understanding the necessary sacrifices. I also couldn't have done it without the love and support from Amy and the Roos. She was the motivation for my success and I will forever be indebted.

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PREFACE

This thesis project was a part of something much larger. It was funded by the USDA-SCRI Grant Award and the project was replicated in Lubbock, TX and Mount Vernon Washington. We also received technical and lab support from Montana State University, Texas Tech University, Texas A&M AgriLife Extension, Washington State University, and Western Washington University.

ABSTRACT

High tunnels extend the production season, and increase fruit quality, yield and crop marketability of high-value crops, but have been underutilized in the Southeast. In this study, organically managed variety trials of two high-value crops, strawberry (*Fragaria* x *ananassa*) and tomato (*Solanum lycopersicum*), were conducted in high tunnel (HT) and open field (OF) production systems to compare yield and quality. Furthermore, specialty crops are commonly grown on black plastic mulch to increase earliness of harvest, fruit quality and yield. However, plastic disposal is time consuming and costly. Degradable mulches reduce removal costs, lessen environmental impacts, and provide functionality during the season. Degradable alternatives to black plastic mulch were compared in HTs and the OF to measure degradability in the production season, weed control, and tomato yield. Yield, size, firmness, color, soluble solids content, titratable acidity, and the ratio of soluble solids content to titratable acidity were evaluated for six strawberry cultivars. These were compared among winter HT, spring HT, and spring OF production systems. Quality was highest in the winter HT system but yields were lowest. The spring OF system produced higher yields, but quality was reduced. Albion attained the best quality among cultivars, while Strawberry Festival produced the highest marketable yield (weight and number of fruit).

A comparison of yield and quality of four tomato cultivars grown in HT and OF systems showed that HTs increased yields compared to the OF. Early Girl had greater yields than the other three cultivars, and Cherokee Purple (CP) had the lowest yields. While lower than other cultivars, CP yields were three times greater in the HT versus the OF production system, and price premiums attained for organic heirlooms can help offset yield differences.

Four degradable mulches (BioAgri, BioTelo, WeedGuardPlus, and an experimental spunbond nonwoven fabric (SB-PLA)) were compared with black plastic and a bare ground control for yield, weed control, and degradability in HT versus OF production systems. WeedGuardPlus, BioAgri and BioTelo performed comparably to black plastic with regard to yield and weed control, while degrading during the production season to potentially provide a more sustainable alternative for specialty crop production.

Table of Contents

List of Tables

Table Page

List of Figures

Introduction: The History of High Tunnels and Their Use

High Tunnel Beginnings

Glass greenhouses were the primary choice for plant production in a protected environment prior to the 1940's and structural designs had not changed much for many decades. Emory M. Emmert of the University of Kentucky lacked funding for a glass greenhouse so he designed a wooden structure covered with stretched cellophane in 1953 (Wittwer, 1993). His design paved the way for the current plastic covered high tunnel. After World War II, plastic sheeting was introduced for agricultural use for greenhouses, rowcovers, and soil mulches (Dalrymple, 1973). Clear plastic replaced Emmert's stretched cellophane and the high tunnel was created. However, this design did not gain interest in the United States for nearly 30 years.

High Tunnel Designs

The high tunnel structure and design varies according to the local climate and the longevity desired in the field (Lamont, 2009). The structure, frame, doors, end walls, types of ventilation (vents, roll-up/down sides), and orientation change depending on the environmental conditions in the region. Several types of high tunnel structures exist and their design determines the time of production and crop produced. All high tunnels are covered with a single or double layer of greenhouse grade plastic (0.10 to 0.15 mm) (Lamont *et al*., 2002; Wells, 1996). They are passively heated and ventilated without the use of electricity, and crops are grown directly in the field soil (Carey *et al*., 2009; Reid, 2009). A north-south orientation allows the maximum amount of sunlight to penetrate the rows and is better suited for summer crops. A north-south orientation maximizes ventilation through sidewalls due to summer westerly winds. An east-west orientation allows maximum southern exposure and better sun penetration into the crop canopy for fall and early spring crops (Reid, 2009).

Common types of high tunnels include hoop-house tunnels or Quonset-style tunnels, Gothic-style tunnels, and multi-bay tunnels. A Quonset-style high tunnel does not usually exceed 9.14 m by 29.26 m. Tunnels wider than 9.14 m do not allow sufficient lateral airflow, but this type of narrow high tunnel is easier to ventilate regardless of the length of the tunnel. Quonset-style tunnels are composed of rounded arches to create a single bay. The pitch of the roof can collect more snow than Gothic-style tunnels and closer hoop spacing is necessary to support heavier snow accumulation. Gothic-style tunnels have peaked roofs, thereby allowing snow to shed better than Quonset-style tunnels. Gothic-style tunnels are taller but require bracing for structural integrity to withstand strong winds (Reid, 2009).

Multi-bay tunnels cover large land areas, many hectares in some cases, and have a sloped roof to allow rainwater to runoff (Lamont, 2009). Multi-bay tunnels are popular in Europe and California and are tall enough to cover fruit trees inside. Multi-bay tunnels are comprised of many single-bay tunnels and are connected by gutters at the seams. These structures do not withstand strong winds or snow loads (Reid, 2009).

Environmental conditions will determine what type of tunnel is used. Quonset-style tunnels may need to have snow removed to avoid heavy loads that would otherwise cause the tunnel to collapse. These serve as a cold frame to over-winter vegetables during winter months and allow for fresh produce during spring, fall, and winter, but the temperature becomes too hot for crop growth in summer months (Coleman, 1999). Gothic-style tunnels are better suited in areas that receive large amounts of snow because the peaked roof sheds snow more easily. The temperature inside the tunnel provides cold protection to crops for continued production (Coleman, 1999). Gothic-style tunnels permit summer production due to the ability to ventilate the structure.

High tunnels are considered non-permanent structures and are theoretically able to be moved from field to field. Many high tunnel structures are secured with cemented, in-ground posts for stability to withstand high winds. Some high tunnels sit on top of the soil and can be moved by simply lifting the tunnel off the ground or by dragging it to a different field site via track or by tractor (Garbos, 2011). Moveable tunnels allow the ability to increase rotation options, reduce the build-up of soilborne diseases, and salt accumulation (Garbos, 2011). However, tunnels that sit on top of the soil are subject to strong winds that can flip or roll them, often destroying the frame and plastic cover, if they are not anchored (Reid, 2009).

Frames may be made of galvanized steel, PVC pipe, or plant material such as bamboo, but the frame choice depends on the environmental extremes experienced. High tunnels constructed with heavy duty piping or steel are typical of multi-bay tunnels, are more permanent, and are able to withstand inclement weather events. High tunnel frames made from PVC pipe or bamboo are much more economical than steel frames, easily moved in the field, but will not withstand high winds (Lamont, 2009).

Most high tunnels have end-walls that are completely removable or opened to allow access for large equipment (Lamont *et al.*, 2002). These open end-walls allow for ventilation. Many high tunnel models also have roll-up or roll–down sides and vents that can be opened to allow for additional ventilation (Lamont *et al*., 2002; Wells, 1996). End walls, side walls and vents are important parts of the high tunnel structural design to control the amount of ventilation, but they also play an important role in temperature modification. During the summer season, end walls, side walls, and vents are left open to allow for maximum ventilation and closed in late fall, winter, and early spring to increase the temperature (Wien, 2009).

Benefits of High Tunnels

High tunnels are becoming more prevalent in the United States due to the year-round demand for high quality, fresh, and local produce (Carey *et al.*, 2009). High tunnels have been found to offer many advantages, including environmental modification, season extension, higher yields, quality improvement, crop protection from severe weather, and the ability to achieve premium prices compared to open field production (Carey *et al*., 2009). Early spring, late fall, and winter production of cool season leafy vegetables is possible in temperate climates in the United States due to increased temperatures from high tunnels (Wells, 1998; Gent, 2002; Jiang *et al*., 2004). High tunnels modify the temperature while extending the growing season for several commodities, such as flowers, vegetables, and small fruits (Orzolek *et al*., 2006; Rasmussen and White, 2006; Lamont, 2009). Using these cost-effective structures created a warmer growing environment for vegetables, flowers, and fruit trees (Jiang et al., 2004; Wells, 1998). The temperatures in high tunnels rose rapidly (10 ^{o}C or more) compared to outside temperatures when there was full sun allowing for optimum growth of tomato and cucumber early and late in the growing season when outside temperatures were too low for growth (Wien, 2009). High tunnels permit crop production during unfavorable seasons in different climates (Jensen and Malter, 1995; Coleman, 1999).

The early maturation of high tunnel crops was found to be caused by increased temperature during the spring growing season (Wells and Loy, 1993). The warmer air temperature allowed for faster accrual of growing degree days and reduced the time period needed for crop maturation if conditions were too cold in the open field (Both *et al*., 2007; Waterer and Bantle, 2000). This advanced yields for up to one month and allows earlier planting in the spring while extending the production season (Medina *et al*., 2009; Knewtson *et al*., 2010). In Washington, high tunnels allowed tomato production, where open field production was virtually non-existent, due to an extremely short production season in the open field for warm season crops (Miles *et al.*, 2012). High tunnels increase crop productivity and earliness allowing for out of season production of high-value crops (Abdul-Baki and Spence, 1992).

High tunnels tend to reduce crop stress and often increase yield relative to the exposed open field (Bumgarner et al., 2011). During the growing season, high tunnels improve light penetration into the plant canopy and cause more uniform distribution of irradiance to the foliage (Kurata, 1992). High tunnel production of strawberries has been found to increase yields two to three times greater than field production, and harvests lasted one month longer where field production declined after initial peak harvest (Burlakoti *et al*., 2013; Portz *et al*., 2010).

Harvests can be extended in high tunnels due to the exclusion from weather events and pests. High tunnels protected plants from wind, hail, rain, insects, and disease producing a higher quality product that is cleaner and uniform in maturity (Wittwer, 1993). The exclusion of weather events allows crops previously damaged by wind, such as watermelon, squash, cucumber, and strawberry, to thrive (Wittwer, 1993). High tunnels allowed for production of lettuce and tomatoes in the High Plains of Texas, where field production was damaged by sand particles abrading the plants and fruit due to high winds (Miles *et al.*, 2012; Wallace *et al.*, 2012).

Insect pressure is reduced in high tunnels compared to the open field due to the plastic covering's ability to reduce UV radiation (Costa *et al*., 2002). By interfering with UV radiation, flying insects are not able to navigate as easily, causing reductions in pest populations and a reduction in chemical applications (Antignus *et al.*, 1996). High tunnels are particularly well suited for organic production because of the decreased pest pressure. Lessening the use of chemicals may allow populations of beneficial organisms to increase and maintain pest populations at levels below the economic threshold (Lamont *et al*., 2003).

The use of high tunnels also helps to reduce foliar diseases by eliminating rain (Orzolek *et al*., 2004). The exclusion of rain helps to prevent soil splash, which limits the spread of soilborne diseases (Mills *et al.*, 2002). High tunnels also are able to reduce humidity and decrease the ability of foliar pathogens to germinate (Xiao *et al*., 2001). High tunnels reduced gray mold on strawberry by as much as 97% compared to the open field (Xiao *et al.*, 2001) and early blight on tomato was reduced two-fold (Rogers and Wszelaki, 2012). Burlakoti *et al.* (2013) found gray mold and anthracnose incidence to be low in high tunnels compared to the open field due to the prevention of disease dispersal from rain.

The exclusion of weather events and decreased disease pressure afforded by high tunnels also extended the shelf-life of small fruit (Lamont *et al.*, 2003; Lamont, 2009). Earlier production, predictable yields, and a longer shelf-life in high tunnels compared to field grown crops allows for more profit potential for the grower (Wittwer, 1993). High tunnels allow growers to sell in markets when prices are at a premium and the market is not inundated with produce (Wells, 1996; Wells and Loy, 1993).

Limitations of High Tunnels

Although high tunnels increase productivity, there are limitations. High tunnels require intensive management and can contribute to adverse temperatures, moisture deficiencies, lower light interception, and exhaust soil nutrients (Wittwer, 1993). Daytime air temperatures inside high tunnels can exceed the outside air temperature by 10 ^{o}C or more on sunny days, and inadequate temperature management can have negative impacts on fruit quality and production (Wien, 2009). Daily temperature has been found to be more critical than the nighttime temperature, affecting pollen production in strawberry and tomato (Bodo, 1991; Peet *et al.*, 1997).

Plants experiencing higher temperatures inside the tunnels require adequate amounts of irrigation. Kuchenbuch *et al.* (1986) found low soil moisture caused a decrease of nutrient transport from the soil to the roots. Reducing nutrient transport to plants has been found to induce physiological disorders, such as radial cracking, blossom end rot, and yellow shoulder in tomato (S. Bogash personal communication). However, excess moisture causes tomato fruit to split or crack prior to harvest (Peet and Willits, 1995). Fruit cracks also develop from sunlight exposure (Emmons and Scott, 1997).

Differences in nutrient uptake occurred in plants in high tunnels versus field production and in systems receiving conventional versus organic fertilizers (Gent, 2002; Zhao *et al*., 2007). Nutrient uptake by plants was more efficient in high tunnels and open fields receiving organic fertilizers (cattle manure, alfalfa hay, and fish emulsion) compared to conventional fertilizers and nutrients were not leached as easily in high tunnels compared to the open field. However, soil salinity was found to be higher in high tunnels but was not found to be detrimental to crops, and the effects on soil quality were influenced by soil management over an eight year study (Knewtson *et al*., 2012).

Soil management can be challenging in high tunnels due to intensive production, which can exhaust soil nutrients, and incorporating cover crops or living mulches into a tunnel rotation is difficult since crop production is year-round (Montri and Biernbaum, 2009). However, an eight year high tunnel study found the percentage of organic matter doubled with the use of organic soil amendments and fertilizers (cattle manure, alfalfa hay, and fish emulsion) compared to cover crops and conventional fertilizers (Knewtson *et al*., 2012). Producers utilizing high tunnel systems must be cognizant of soil health and incorporate organic matter and/or composts, which help to build microbial biomass in high tunnels and are used as a substitute for cover crops (Millner *et al*., 2009).

Conclusions

High tunnels offer the potential for season extension and/or year-round production and the ability to attain price premiums. High tunnel structures vary in their design and features, allowing for tailoring to the climate and crop needs. The exclusion of severe weather events lessens disease pressure and provides protection for increased crop quality and yield. The UV-interfering plastic cover disorients flying pests and helps reduce their populations. In some climates and under extreme environmental conditions, HTs allow for production of crops that are otherwise extremely difficult to grow, (e.g., strawberries in the Texas High Plains, tomatoes in the Pacific Northwest). While high tunnels are not without their limitations, the benefits outweigh the limitations.

Chapter 1:

The Influence of Organically Managed High Tunnel and Open Field Production Systems on Strawberry (*Fragaria* x *ananassa)* Quality and Yield

Abstract

The seasonal production and quality of six strawberry (*Fragaria* x *ananassa*) cultivars grown organically in both high tunnel and open field production systems were compared. In addition to yield, berries were evaluated for average size, firmness, color (L* a* b*), soluble solids content, titratable acidity, and the ratio of soluble solids content to titratable acidity. Yield and quality traits were compared among winter high tunnel, spring high tunnel, and spring open field production systems. Cultivar and production system affected average berry size, firmness, L*, a*, b*, soluble solids content, titratable acidity, and the soluble solids content to titratable acidity ratio. Berries grown in the winter HT production system (lower temperatures, lower PAR levels, and reduced irrigation) showed improved quality traits in all six strawberry cultivars. However, yield per plant was higher in the spring open field system compared to both winter and spring high tunnel production systems.

Introduction

Strawberry (*Fragaria* x *ananassa*) fruit quality is based on sweetness, acidity, astringency, bitterness, aroma, appearance, firmness, and nutritional value (Kader, 1991; Salame-Donoso *et al*., 2010). Temperature, light intensity, water and nutrient availability, and cultivar affect fruit quality and yield (Anagnostou and Vasilakakis, 1995; Himelrick and Galletta, 1990; Kader, 1991; Kadir *et al*., 2006). Strawberry plants are responsive to changes in these environmental conditions (Avigdori-Avidov, 1986), and conditions created by high tunnels have the ability to improve strawberry fruit quality and yield. High tunnels increase temperature, decrease the amount of UV radiation, exclude rainfall, allow control over irrigation, and prevent leaf wetness. This environmental modification extends the harvest season to periods when market prices are higher, providing a higher return to the grower (Gaskell, 2004).

High tunnels have been shown to increase daytime temperatures allowing late fall, early winter, and early spring production of strawberries (Wang and Camp, 2000; Paranjpe *et al*., 2003). The lower overall temperatures during these seasons compared to summer temperatures are conducive to increased fruit quality, yield, and improved earliness (Kadir *et al*., 2006). Temperatures below 30 ^{0}C enhance soluble solid content (SSC) (MacKenzie *et al.*, 2011) and fruit firmness (Anagnostou and Vasilakakis, 1995), but have not been found to affect the color of strawberry fruit or titratable acidity (TA). Although high tunnels offer the ability to increase daytime temperatures during the off-season, light intensity is reduced and this can also alter fruit quality characteristics.

High tunnels decrease the amount of photosynthetic radiation plants receive due to the plastic covering the frame. Krizek *et al.* (2005) found wavelengths between 450 and 700 nm were reduced by as much as 30 to 45% due to a plastic covering.   Strawberries grown with lower levels of light intensity have been found to contain SSC values as high as 11.5% compared to those grown with higher levels of light intensity whose SSC values were reduced to 4.5% (Anagnostou and Vasilakakis, 1995).   Conversely, darker red color and higher TA levels were achieved with an increase in light intensity (Anagnostou and Vasilakakis, 1995; Wang and Camp, 2000), but firmness was not affected (Saks *et al.*, 1996). Sharma *et al.* (2006) found plants grown in reduced light intensity had lower yield and smaller fruits when compared to plants grown in the open field. They found open field plants achieved greater yields while having a shorter harvesting period than those grown in reduced light intensity. Although high tunnel plastic decreases light intensity, the plastic also excludes rainfall which can reduce disease pressure by keeping the plant canopy dry compared to the open field.

Irrigation control allows for the ability to increase water stress resulting in increased SSC (Gerhmann, 1985; Voca *et al.*, 2007), but also reduced red color in fruit (Terry *et al.*, 2007). Reduced irrigation levels have not been found to affect fruit firmness when compared to adequately watered, non-stressed plants (Miller *et al.*, 1998).   However, Kruger *et al.* (2002) found irrigated strawberry plots had reduced fruit firmness when compared to non-irrigated control plots, but the irrigated plots had larger yields.

This study evaluates the cultivar differences and environmental factors affecting strawberry fruit production and quality when grown organically in different seasons of the year under high tunnel and open field production systems.

Materials and Methods

The field trial was conducted during the fall and winter 2011 in the high tunnel (HT) production system and the spring 2012 production seasons in HT and open field (OF) production systems at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN. Elevation at Knoxville, TN is 270 m; soil type is Dewey silt loam with a soil pH of 6.8 and organic matter averaged 1.3%. The study was conducted as a completely randomized split-plot design with production system (HT or OF) as main-plots replicated four times and strawberry cultivars as sub-plots.

Four HTs (29.3 m long by 9.1 m wide) were erected at the site in spring 2010 (Golden Pacific Windjammer Series 5000; Golden Pacific Structures, Cincinnati, OH). The plastic covering on the HTs was Durafilm Super 4 (AT Films, Inc., Edmonton, Alberta, CA) with 92% optical transmission. The HTs were oriented North to South and located 3.2 m apart West to East. Four corresponding OF sites (29.3 m long by 9.1 m wide) were created to the East of the HTs and were also oriented North to South located 3.4 m apart West to East. The plots were spaced to prevent shading form HTs onto OF plots, due to field constraints.

Six sub-plots (one per cultivar) measuring 4.3 m long by 0.6 m wide were assigned within each main-plot and strawberries were transplanted on 23 (HT) and 29 September (OF) with 28 plugs per cultivar in two staggered rows per bed (30.5 cm in- and between-rows). Cultivars tested included three day-neutral cultivars (Albion, San Andreas, and Seascape) and three June-bearing cultivars (Chandler, Radiance, and Strawberry Festival) (Norton Creek Farms, Cashiers, NC).

Pre-plant organic fertilizer (Soybean Meal: 7.00 total N, 0.40 elemental P, 0.66 elemental K, Foothills Farmers Co-Op, Maryville, TN) was applied to deliver an estimated 33.63 kg N per hectare. The sub-plots were rototilled (Kubota Tractor Corporation; model B7510; Torrance, CA). Drip irrigation (T-Tape, low flow, 16 mm diam., 8 mm, 30-cm emitter spacing, San Diego, CA) was laid in the center of each bed beneath a single layer of black polyethylene plastic mulch (0.03 mm embossed; Pliant Corp., Schaumburg, IL). Due to HT constraints, the mulch was laid by hand onto flat beds in the HTs. In the OF plots, the mulch was laid with a Holland plastic layer (Holland Transplanter Co., Holland, MI) onto flat beds behind a John Deere 5225 tractor (Deere & Company; Moline, IL).

All plots were monitored weekly for insects, diseases, and fertility via direct observation. Three plants were randomly chosen in each sub-plot and monitoring was limited to one minute or less per plant. Single nozzle sprayers were used to apply pest control products using a SOLO 430-1G handheld sprayer (Newport News, VA, U.S.) as needed in the HTs. Potassium salts of fatty acids (49 % a.i. (M-Pede; Gowan Company, Yuma, AZ)) at label rate of 0.03 ml per liter a.i. was applied 1 November 2011 to control silverleaf whiteflies (*Bemisia argentifolii*) and 6 January and 24 February 2012 to control the tarnished plant bug (*Lygus lineolaris*). Azadirachtin (1.2 % a.i. (Aza-Direct;Gowan Company, Yuma, AZ)) at label rate of 12 ml per liter a.i. was applied 2 and 9 March 2012 and a combination of M-Pede (label rate of 0.03 ml per liter a.i.) and Aza-Direct (label rate of 12 ml per liter a.i.) was applied 23 March and 11 April 2012 to control the tarnished plant bug. Predatory mites (*Neoseiulus californicus*) (3- 100 ml bottles containing 5,000 mites per bottle) (Koppert Biological Seasons, Inc., Howell, MI) were released 27 March, 3 and 12 April 2012 in the HTs to control the two-spotted spider mite (*Tetranychus urticae*). A class C large earth bumblebee (*Bombus terrestris*) hive (Koppert Biological Seasons, Inc.-USA; Howell, MI) was placed in each high tunnel 10 November 2011, 23 February 2012, and 3 April 2012 for supplemental pollination.

Strawberry plants were irrigated once (12.7 mm per application) or twice per week as needed based on the soil moisture conditions, beginning at transplanting and continuing until harvest. Soil moisture was determined by touch-testing the soil to determine the amount of moisture in the top 7.62 cm of soil. Crops were fertilized bi-weekly through the drip system with Schafer's Liquid Fish (2.00 total N, 0.40 elemental P, 0.17 elemental K) at a rate of 0.91 kg N per hectare per day.

Microclimate data were recorded with a weather station (Hobo Weather Station Data Loggers; Onset Computer, Bourne, MA). Due to the high cost of the weather monitoring equipment, only one HT and one OF plot were monitored. Minimal variation within HT and OF system replications likely existed due to their close proximity to each other. Measurements included average high/low air temperatures (^{o}C), photosynthetically active radiation (PAR, $\mu mol \cdot m^{2} \cdot s^{-1}$), rainfall (inches converted to mm), and relative humidity recorded at 15-min intervals. Environmental conditions were observed from transplant to final harvest. Environmental conditions for 21 days leading up to quality harvests during the winter, and 14 days leading up to quality harvests in the spring were used to determine environmental influences on fruit quality; the interval for berry ripening in each respective season and the stage at which berry quality is most influenced by the environment (D. Deyton personal communication).

Fruit harvests in the winter HT plots began 2 December 2011 and continued until 12 January 2012, and quality data were collected from harvests on 21 and 29 December. Fruit quality was measured on 20 berries from each subplot/cultivar. Only 15 berries were tested in the winter HT due to the low number of fruit. 'Chandler' and the second HT replication did not bear adequate numbers of fruits in the winter for quality sampling. Strawberry fruits were harvested once per week in the winter and twice per week in the spring. Spring HT and OF strawberry fruit quality was measured during peak harvest. Peak harvest was determined by visual assessment of plots, fruit set, and flower set. Spring harvests began in the HT plots 2 March and continued until 14 June, and quality data were collected 27

March. In the OF plots, harvests began 6 April and continued until 29 June, and quality data were collected 24 April.

Quality measurements included color, firmness, soluble solids (SSC), and titratable acidity (TA). Fruit color was measured with a MiniScan XE PLUS Spectrophotometer (Hunter Associates Laboratory, Inc., Reston, VA) in L*a*b* mode under CIE Standard Illuminant C. Two readings per fruit were taken on opposite sides of the berry and averaged for both color and firmness data. Fruit firmness was measured with a Wagner Force Dial ™- Model FDK 32 (Wagner Instruments, Greenwich, CT) with a 3-mm tip. For determination of SSC and TA, juice was extracted from a composite of four fruit for each of five samples per replication per cultivar. When the 20 fruit target was not reached, a minimum of 15 fruit was used for quality measurements. Of the 15 fruit, a composite of three fruit was used to achieve five samples. SSC was measured with a temperature compensating digital refractometer (AR200 Automatic Digital Refractometer; Reichert, Inc., Depew, NY). TA was determined by manual titration using 0.1% NaOH to an endpoint pH of 8.1 (Calibration Check ™ Portable pH/ORP Meter, HI 9126; Hanna Instruments, Inc., Woonsocket, RI). TA was calculated using citric acid to determine acid equivalents.

Statistical analyses. Statistical analyses compared main effects and interactions of production system/season (PS) and cultivar (C). All data were subjected to analysis of variance (ANOVA) using PROC MIXED (SAS version 9.3; SAS Institute, Cary, NC). Data were analyzed as a completely randomized split-plot design. All means were separated using Fisher's least significant difference test (α = 0.05).

Results and Discussion

Main effects of production system/season, cultivar, and their interaction affected strawberry fruit quality and yield. Berries from the winter HT season attained higher values for all quality components measured (larger berry size, higher firmness, L*, a*, b*, SSC, TA, and SSC:TA) compared to the spring HT system (Table 1). Winter HT berries also outperformed spring OF berries for all quality components except TA. Between spring production systems, berries from OF plots had higher a*, b*, SSC, TA, and SSC:TA levels compared to berries from HT plots.

Environmental conditions during fruit ripening largely influenced strawberry fruit quality (Rutkowski *et al*., 2006). During this study the plants experienced an unusually warm winter and early spring (March) during fruit quality testing in the HT. However, April proved to be much cooler coinciding with quality testing in the OF (Fig. 1). Quality traits varied among each production season and among the cultivars, which is in agreement with the findings of Wang and Camp (2000), who found plant growth and development of fruit to be affected by cultivar and the variation in environmental conditions. They found that lower temperatures decrease the rate of ripening for all cultivars while causing the fruits to be larger and of better quality. Their findings coincide with findings from the winter HT production season reported here (Table 1). Higher temperatures during development created more variability among cultivars with regard to fruit quality as seen in the spring HT and OF production seasons (Fig. 1).

Differences in average berry size, firmness, a*, b*, SSC, TA, and SSC:TA occurred among cultivars when averaged across all three production seasons (Table 2). Albion had the largest average berry size, but did not differ from the other cultivars except San Andreas. San Andreas had the firmest fruit but did not differ from the other cultivars except Radiance. San Andreas had higher a* and b* values than all other cultivars, and had higher TA than all cultivars except Seascape. Albion, Seascape, and Strawberry Festival had the highest SSC ranging from 7.5 to 7.9. However, Radiance and Strawberry Festival had higher SSC:TA than the other three cultivars, with San Andreas having the lowest ratio.

Interactions between cultivar and production season varied in all quality parameters except TA which had a range from 0.47 to 0.78 (Table 3). Albion was consistently one of the largest berries across cultivars among all three seasons; other parameters, however, did not show clear trends for cultivars across production systems and seasons.

During fruit ripening of the winter HT production season, the average temperature was lower than both spring HT and OF (Fig. 1). Rutkowski *et al.* (2006) found firmness to be strongly influenced by temperature during the red-ripening stage of fruit development, and correlates with my findings and those of Anagnostou and Vasilakakis (1995) that increased temperatures cause a decline in the firmness of fruit. The firmness among cultivars within winter HT and spring HT and OF varied, indicating cultivar genetics also plays a role depending on the type of growing environment during fruit ripening. Overall, San Andreas, Albion, and Seascape had the firmest berries in the winter HT production system. Chandler was the least firm among the cultivars in both spring HT and OF production seasons. San Andreas, Albion, Radiance, and Strawberry Festival were the firmest fruit for spring HT production while Strawberry Festival had the firmest fruit for spring OF production. This study reinforces earlier findings that increasing temperatures and genetic differences between cultivars can cause a decline in fruit firmness.

Temperatures during fruit development also have an influence over SSC and TA in strawberry. As temperatures during fruit ripening increase, SSC, TA, and SSC:TA decrease (Wang and Camp, 2000). Wang and Camp (2000) found temperatures above 30 ^{o}C reduced strawberry fruit SSC, TA, and SSC:TA. My study supports those findings as spring HT maximum average temperature reached 32.8 ^{o}C (Fig. 1), and temperatures exceeded 30 ^{o}C eleven of fifteen days during the fruit ripening stage. Winter HT and spring OF remained below the 30 ^{o}C threshold during the fruit ripening stage. All cultivars consistently expressed the lowest levels of SSC and SSC:TA in spring HT compared to spring OF and winter HT (Table 3), and the winter HT production season had higher levels of SSC and SSC:TA (Table 1). Therefore, I found increasing temperature during ripening correlated with decreasing SSC. Temperatures in March were unusually warm during berry ripening which coincided with quality testing in the spring HT system. Temperatures then cooled during berry ripening for quality testing for spring OF in April. This increase in temperature in March may have caused the spring HT SSC to decrease by 3.3% as compared to spring OF.

Seascape and Albion consistently achieved some of the highest SSC for winter HT, spring HT, and spring OF (Table 3). Radiance and Strawberry Festival expressed the lowest TA levels when averaged across production seasons (Table 2). The SSC:TA differed among production seasons and cultivars (Table 3). Winter HT had the highest SSC:TA followed by spring OF, and spring HT had the lowest ratio (Table 1). Within each production season, Radiance and Strawberry Festival consistently had high SSC:TA (Table 3) indicating that environmental manipulation also influences the balance of SSC to TA. High SSC levels are best paired with high TA levels to achieve a high quality of flavor (Kader, 1999). Rutkowski *et al*. (2006) found strawberry fruit quality to be positively correlated with SSC:TA, which is in agreement in this study.

In addition to temperature, strawberry fruit quality is influenced by light intensity measured by photosynthetically active radiation (PAR) during fruit ripening. Anagnostou and Vasilakakis (1995) correlated rising levels of light intensity with rising levels of TA and decreasing levels of SSC in strawberry fruit. During the winter HT production season, the lowest levels of PAR were measured followed by the spring HT and OF production seasons, respectively (Fig. 2). HT PAR levels were low due to the overall lower levels of natural light during the winter HT production season (December) and the plastic covering over the HT which further limits the amount of UV radiation. In the spring HT season, the plastic cover decreased the amount of PAR received compared to the spring OF, which had no cover and, therefore, no reduction in light intensity. In addition to differences in TA and SSC, changes in PAR likely contributed to differences between production seasons in relation to color parameters (L*, a*, and b*) (Table 1).

The winter HT production system had the lowest PAR levels and had berries with the highest-levels of L*, a*, and b* indicating that the fruit are seen as a bright orange-red. The spring HT production system PAR levels were in between the winter HT and spring OF, and the spring HT berries had the lowest levels of a* and b* indicating darker, blue-red fruit. The spring OF production system had the highest PAR levels and berries had slightly higher levels of a* and b* indicating intermediate red fruit. These findings contradict earlier reports that high levels of light intensity cause fruit to achieve brighter color values. Within the two HT production seasons, L*, a*, and b* values differed among cultivars (Table 3). Berries from the spring OF production system received the greatest amount of PAR, and showed minimal differences in L*, a*, and b* across cultivars. In all production seasons, Strawberry Festival contained the lowest a* levels indicating a slightly less red fruit while San Andreas had the highest a* levels indicating greater red color. L* and b* levels did not display any clear relationships among cultivars (Table 3). Strawberry Festival attained the highest L* value in the winter HT production system and was greater than all other cultivars except Radiance. San Andreas had the highest L* value for spring HT production system and Albion had the highest L* value for spring OF production system. San Andreas had the highest a* value in the winter HT production system bud did not differ from the other cultivars except Strawberry Festival. San Andreas and Chandler had the highest a* and b* values in spring HT production system. San Andreas and Albion had the highest a* value and the highest b* value along with Seascape and Strawberry Festival in spring OF production system. Diverse levels of light intensity may have caused different reactions among cultivars concerning color expression.

From this study, light intensity was found to be correlated to SSC, with lower PAR levels potentially contributing to an increase in SSC, but TA did not display similar trends. Berries from the winter HT system had higher SSC and TA levels followed by spring OF and spring HT (Table 1). PAR differences for spring OF and HT (Fig. 2), however, revealed the inverse where high PAR levels received in the spring OF production system resulted in berries with higher SSC levels than the spring HT production system that received lower PAR levels (Table 1), and is contrary to earlier findings that lower levels of PAR increase SSC (Anagnostou and Vasilakakis, 1995). Temperature seems to play a larger role affecting SSC and TA than light intensity. Anagnostou and Vasilakakis (1995) reported that high TA levels are achieved with high PAR levels, but Antognozzi *et al.* (1995) and Tombesi *et al.* (1993) found that kiwifruit had the same TA levels regardless of the amount of light intensity received. The results from our study also show no differences in TA regardless of light intensity (Table 3).

SSC is affected by temperature (MacKenzie *et al.*, 2011), cultivar (Kader, 1991), and water stress (Gerhmann, 1985; Voca *et al.*, 2007). Crisosto *et al.* (1994) found in peaches that treatments receiving less than optimal irrigation caused SSC to be higher when compared to treatments receiving adequate irrigation and supports an earlier report that found water stress to cause SSC to increase in peach orchards (Veihmeyer and Hendrickson, 1949). Each production system in each season received differing amounts of irrigation prior to quality testing (Table 8). Winter HT berries had the highest mean SSC (Table 1) followed by spring OF and spring HT, which corresponds to the amount of water received in each production season (Table 8). Albion, Seascape, and Strawberry Festival achieved the highest SSC levels in all three production seasons and San Andreas and Radiance maintained the lowest SSC levels (Table 3). Cultivars vary according to levels of water received but maintain higher or lower base levels of SSC according to their genetics. While water stress has the ability to increase SSC (Gerhmann, 1985; Voca *et al.*, 2007) water stress has been shown to reduce red fruit color (Terry *et al.*, 2007). Results showed that contrary to an earlier study by Terry *et al.* (2007), red color was highest and/or greatest in the winter HT system that received the least amount of water.

Irrigation also affects fruit firmness, and Kruger *et al.* (2002) found irrigated strawberry plots to express reduced firmness and was true in this study when comparing the spring and winter production seasons (Table 1). Winter HT system received the least amount of irrigation and produced the firmest berries while the spring production systems received more irrigation and produced softer berries (Table 8). Within production systems Radiance had the lowest fruit firmness than all other cultivars in the winter HT production system. Chandler had the lowest fruit firmness in both spring HT and OF. These findings further prove how environmental factors influence fruit quality.

Yield is also affected by environmental and genetic factors. Total strawberry weight per plant is estimated between 0.39 and 0.65 kilograms per plant in an annual hill plasticulture system in the southeastern U.S. (Southeastern Plasticulture Strawberries, 2011). In 2011, North Carolina growers averaged 0.34 kilograms per plant while Florida growers averaged 0.64 kilograms per plant (USDA, 2012). In the 2012 study, we averaged 0.05 kilograms per plant for total yield in the winter HT production system, 0.34 kilograms per plant in the spring HT production system, and 0.42 kilograms per plant in the spring OF production system (Table 4). The combination of the total yield by weight for winter and spring HT yielded 0.39 kilograms per plant (Table 5). These results are on the low end of estimated berry weight per plant. Reasons for low total yields are attributed to plant stress due to winter berry production in the HT system, high winter temperatures, substantial temperature fluctuations, and low fertility.

Fluctuating environmental conditions affected strawberry yield throughout the production seasons. Among production seasons, spring OF plots yielded the greatest number and weight of total and marketable berries compared to winter and spring HT plots (Table 4), and supports earlier findings of Dufault and Ward (2009a). Spring HT outperformed the winter HT regarding total and marketable number and weight of berries. Forcing strawberries to bear fruit during winter months can be a drawback as yield is reduced compared to traditional spring production (Dufault and Ward, 2009b). Reduced yields result from the use of stored carbohydrates during winter production. Dufault and Ward (2009b) reported greater berry weight in winter HT production compared to spring HT production and was reinforced in this study (Table 1).

Total and marketable yield differences among cultivars existed when averaged across all three production seasons (Table 6). Chandler and Strawberry Festival had the highest number of total berries per plant. Radiance and Strawberry Festival had the highest total kilograms of berries per plant. Strawberry Festival had the highest marketable yield, and out-yielded all other cultivars in number and pounds of berries per plant except for Chandler and Radiance, respectively.

Interactions between cultivar and production season varied for total and marketable yield (Table 7). Strawberry Festival consistently yielded the greatest number and weight of berries per plant for both total and marketable yield in the spring OF. However, Chandler spring HT production was similar for total number of fruit, while Radiance and San Andreas in spring OF production and Radiance in spring HT were similar regarding total weight. The winter HT system yielded the lowest total and marketable number of berries and kilograms per plant, and yields did not differ among cultivars. The top yielding cultivar in the spring HT system for total and marketable number of berries was Chandler, but Radiance yielded the greatest by total and marketable weight. This indicates that Chandler produced more small berries while Radiance produced fewer but larger berries. Although winter and spring HT systems produced lower yields than the OF system, total and marketable yield by number and weight did not differ when both HT seasons were combined and compared to the OF season (Table 5). Yield was found to be affected by environmental factors experienced during ripening and throughout the production season.

Light intensity may have an effect on yield when comparing spring production systems. The findings from this study support an earlier report (Sharma *et al.*, 2006) that plants grown in reduced light intensity produce lower yields (Table 4). The OF plants had a reduced harvesting period (84 days) compared to HT plants (104 days) and OF plants yielded more fruit. However, this study does not support their findings that light intensity affects berry size (Table 1). Increased light intensity may have benefited OF yields while shortening the harvest period, but light intensity is one of several environmental factors influencing yield.

Spring OF production system berries received the most irrigation through rainfall and supplemental irrigation throughout the production season when compared to spring HT and winter HT production system's (Table 9). Irrigated strawberry plots were found to attain greater total yields and fruit weight than lesser irrigated plots (Kruger *et al.,* 2002). In this study, total number of berries and total berry weight was greatest for the spring OF (Table 4), which received the most irrigation during the harvest period.

Apart from environmental conditions and irrigation affecting yield, insect damage and disease caused total and marketable yields to be reduced in the HT production system. The primary reasons for unmarketability in the HT and OF system were insect damage caused by the tarnished plant bug (*Lygus lineolaris*) and gray mold caused by *Botrytis cinerea* (Table 10). The tarnished plant bug feeds on strawberry flowers and the hilum causing distorted, unmarketable berries. Warm winter temperatures provided these insects an overwintering location in the HTs and caused more damage to berries during winter and spring HT production. The insect resumed feeding in the spring and populations established in OF plots as flowers began to initiate. This insect was difficult to control and caused significant damage to both strawberry flowers and fruits. The winter HT received the greatest damage with two-thirds of the unmarketable yield affected by the tarnished plant bug (Table 10). Half of the unmarketable fruit from the spring HT was a result of this insect, and one-third of unmarketable fruit was affected by this insect in spring OF. However, gray mold was the primary reason for unmarketability in the spring OF and accounted for 36% of unmarketable berry numbers and 44% of unmarketable berry weight. Only 11% of spring HT unmarketable berries and 14 % of unmarketable berry weight was infected by *Botrytis cinerea*. Gray mold causes harvest losses of strawberries due to premature rot. Gray mold is amplified by warm temperatures and high humidity (Williamson *et al.*, 2007). These conditions occurred in both the spring HT and OF plots allowing for *Botrytis cinerea* infection during the harvest periods (Fig. 3). However, protection from overhead irrigation seemed to protect the plants from this disease, to some degree. Conditions were not conducive for *Botrytis cinerea* infection during the winter HT season and no fruits were infected during the harvest period.

This study strengthens earlier results that environmental factors and cultivar strongly influence strawberry fruit quality and yield. It also provided strong evidence that production system (HT vs. OF) in combination with the environment and cultivar impacts quality traits and yield. While some variations are inherent genetic differences, others are greatly influenced by environmental manipulation.

Albion attained the best quality- large berry size, greater firmness, deep red color, high SSC, and high SSC:TA- in all three production systems. However, Albion yielded the least berries in both the spring HT and OF production systems. Strawberry Festival yielded the most total and marketable berries in the winter HT and spring OF production systems, and its quality was comparable to that of Albion. Chandler yielded the most total and marketable berries in the spring HT production system, but had significantly lower quality than all other cultivars.

The spring OF yielded the most berries per plant each season when compared to the winter and spring HT. HTs create an environment favorable for growing high quality strawberries during the cool season. During the unusually hot spring, however, HTs created an unfavorable environment, as temperatures became too hot, too quickly causing strawberries to stop producing new fruit and have lower quality. Strawberries grown in the OF during the spring had good quality due to the decrease in temperatures during their ripening period compared to the HTs, but OF strawberries can be more difficult to manage due to less control of critical environmental components, such as rainfall and unseasonably cool weather. The production season and market will determine which variety and production system should be used to maximize quality and yield.

Growers must identify their season and market and determine which cultivars provide the quality and yield desired and how those cultivars perform when grown in a high tunnel or open field, during the winter or spring. Wholesale markets demand firmer fruit to withstand shipping while direct markets may tolerate softer fruit. The cool season market is especially influenced by weather conditions, and the HT production system will allow for more control over factors, such as temperature, irrigation, and light intensity. The combination of the environment and production system will significantly influence fruit quality. HTs protect against severe environmental conditions but may hinder quality if conditions are unreasonably warm. HTs allow for high quality winter strawberry production outside of the normal strawberry production season, which allows growers to receive market premiums. However, in this study, HT spring production was curtailed due to the unusually warm environmental conditions causing lower quality in 2012. Due to the reduced supply of local strawberries in this region during early spring, the lower yields could potentially be offset by higher prices in the market. High quality and high production were achieved in the OF. Therefore, a producer could start the season in the HT and end in the OF to capitalize on quality, production, and profit.

Appendix: Chapter 1

Table 1. Influence of production system on fruit quality traits of six cultivars of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

Production Season	Average Berry Size[z] (grams)	Firmness (grams)	L*	a*	b*	SSC (%)	TA (%)	SSC:TA
Winter HT	25.23 a	293.1 a	30.991 a	35.061 a	15.023 a	9.42 a	0.70 a	13.64 a
Spring HT	13.32 b	171.7 b	26.796 b	24.772 c	10.471 c	5.53 c	0.60 b	9.32 c
Spring OF	14.18 b	179.2 b	24.479 b	26.395 b	11.934 b	8.63 b	0.66 a	10.90 b
P value	*<.0001*	*0.0002*	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*0.0074*	*<.0001*
LSD $_{(0.05)}$	2.84	36.7	1.028	1.426	0.903	0.74	0.05	0.67

[z] Average berry size data were rank transformed. Means presented are back-transformed.
[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).

Table 2. Influence of cultivar on fruit quality traits of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

Cultivar	Avgerage berry size[z] (grams)	Firmness (grams)	L*	a*	b*	SSC (%)	TA (%)	SSC:TA
San Andreas	15.88 b	245.5 a	27.932	31.240 a	12.669 a	6.8 b	0.72 a	9.35 c
Albion	20.41 a	226.8 ab	27.172	27.834 b	11.566 b	7.8 a	0.68 b	11.51 b
Seascape	17.86 ab	226.9 ab	27.730	28.091 b	11.850 b	7.9 a	0.72 a	10.90 b
Chandler[Y]	.	.	.	.	.	.	.	.
Radiance	18.43 ab	213.8 b	27.702	28.687 b	11.409 b	6.8 b	0.53 d	12.72 a
Strawberry Festival	16.73 ab	234.4 ab	28.395	25.844 c	11.800 b	7.5 a	0.58 c	12.91 a
P value	*0.0037*	*<.0001*	*0.4075*	*<.0001*	*0.0473*	*<.0001*	*<.0001*	*<.0001*
LSD $_{(0.05)}$	4.25	21.8	1.151	1.701	0.791	0.4	0.04	0.67

[z] Average berry size data were rank transformed. Means presented are back-transformed.
[Y] Data for Chandler were not included due to inadequate production and exclusion from quality measurements during the winter HT season.

Table 3. Interaction of production system and cultivar on fruit quality traits of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

	Avg. berry size[Z] (grams)	Firmness (grams)	L*	a*	b*[Y]	SSC[X] (%)	TA (%)	SSC:TA
Winter HT								
San Andreas	20.70 cde	347.0 a	29.876 bc	36.816 a	15.636 a	8.79 b	0.78	11.39 de
Albion	30.62 a	306.4 ab	28.859 cd	35.312 ab	14.738 a	9.85 a	0.68	14.40 b
Seascape	23.53 bcd	330.2 ab	31.181 b	34.594 ab	15.464 a	9.84 a	0.77	12.88 c
Chandler[W]	.	.	.	.	.	.	.	.
Radiance	28.92 ab	242.6 c	31.662 ab	34.657 ab	14.045 a	9.22 ab	0.58	15.94 a
Strawberry Festival	24.66 abc	299.7 b	33.744 a	33.141 b	15.661 a	9.60 ab	0.66	14.52 b
Spring HT								
San Andreas	11.91 f	182.9 de	28.272 cde	28.831 c	11.899 b	5.31 gh	0.69	7.71 j
Albion	14.18 ef	184.1 de	26.264 fg	22.035 fg	9.750 de	5.98 fg	0.64	9.37 ghi
Seascape	14.46 ef	155.8 ef	26.107 fg	23.754 ef	9.768 de	6.30 ef	0.66	9.54 ghi
Chandler	12.19 f	121.8 f	27.479 def	27.798 cd	11.009 bc	5.12 hi	0.62	8.36 ij
Radiance	12.76 f	197.1 cd	26.157 fg	25.534 de	10.537 cd	4.55 i	0.47	9.73 fgh
Strawberry Festival	14.74 ef	188.6 de	26.494 efg	20.681 g	9.864 de	5.94 fg	0.53	11.23 e
Spring OF								
San Andreas	15.59 ef	206.7 cd	25.646 fg	28.074 cd	10.471 cd	6.32 f	0.71	8.94 hi
Albion	16.73 def	189.9 de	26.394 efg	26.155 cde	10.211 cde	7.59 c	0.70	0.76 ef
Seascape	15.59 ef	194.6 cde	25.902 fg	25.926 de	10.318 cde	7.45 c	0.72	10.29 efg
Chandler	11.06 f	128.6 f	25.447 g	24.294 ef	9.260 e	7.38 cd	0.74	9.95 fgh
Radiance	13.89 ef	201.7 cd	25.285 g	25.870 de	9.644 de	6.73 def	0.54	12.48 cd
Strawberry Festival	11.34 f	214.9 cd	24.947 g	23.708 ef	9.874 cde	7.04 cde	0.55	12.97 c
P value	*0.0057*	*0.0025*	*0.0027*	*0.0170*	*0.0359*	*0.0077*	*0.2395*	*0.0206*
$LSD_{(0.05)}$	7.09	44.4	2.016	2.947	1.426	0.88	0.08	1.17

[Z] Average berry size data were rank transformed. Means presented are back-transformed.
[Y] b* data was log transformed. Means presented are back-transformed.
[X] SSC data were log transformed. Means presented are back-transformed.
[W] Data for Chandler were not included due to inadequate production and exclusion from quality measurements during the winter HT season.

Table 4. Influence of production system total, marketable, and percent marketable yield of six cultivars of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee Education Center Organic Crops Unit in Knoxville, TN.

Production System	Total yield (no./plant)	Total yield (kg/plant)	Market. yield (no./plant)	Market. yield (kg/plant)	% Market. yield (no./plant)	% Market. yield (kg/plant)
Winter HT	1.9 c	0.05 c	0.8 c	0.02 c	34 b	40 b
Spring HT	32.2 b	0.34 b	15.1 b	0.20 b	46 ab	56 a
Spring OF	35.7 a	0.42 a	20.5 a	0.28 a	57 a	65 a
P value	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*0.0115*	*0.0062*
$LSD_{(0.05)}$	2.5	0.04	3.7	0.05	13	13

[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).

Table 5. Influence of production system total, marketable, and percent marketable yield of six cultivars of organically grown strawberry in winter high tunnel production 2011 and spring high tunnel production 2012 versus open field production 2012 at the University of Tennessee Education Center Organic Crops Unit in Knoxville, TN.

Production system	Total yield (no./plant)	Total yield (kg/plant)	Market. yield (no./plant)	Market. yield (kg/plant)	% Market. yield (no./plant)	% Market. yield (kg/plant)
High tunnel (winter &spring)	34.1	0.39	15.9	0.22	46	55
Open field (spring)	35.7	0.42	20.5	0.28	57	65
P value	*0.2942*	*0.1507*	*0.0588*	*0.1086*	*0.0652*	*0.0936*
$LSD_{(0.05)}$	3.3	0.05	4.9	0.08	12	13

[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).

Table 6. Influence of cultivar on total, marketable, and percent marketable yield of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

Cultivar	Total yield (no./plant)	Total yield (kg/plant)	Market. yield (no./plant)	Market. yield (kg/plant)	% Market. yield (no./plant)	% Market. yield (kg/plant)
San Andreas	20.3 c	0.26 c	10.5 c	0.16 b	43 bc	49 bc
Albion	14.1 d	0.21 d	7.0 d	0.11 c	47 ab	54 ab
Seascape	15.4 d	0.21 d	8.0 cd	0.13 bc	47 ab	54 ab
Chandler	31.6 a	0.28 bc	15.3 ab	0.16 b	37 c	44 c
Radiance	27.3 b	0.34 a	14.6 b	0.22 a	52 a	61 a
Strawberry Festival	31.1 a	0.31 ab	17.3 a	0.20 a	49 ab	59 a
P value	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*0.0008*	*0.0005*
$LSD_{(0.05)}$	3.1	0.05	2.6	0.04	7	8

[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).

Table 7. Interaction of production system and cultivar on total, marketable, and percent marketable yield of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.						
	Total yield (no./plant)	**Total yield (kg/plant)**	**Market. yield (no./plant)**	**Market. yield (kg/plant)**	**% Market. yield (no./plant)**	**% Market. yield (kg/plant)**
Winter HT						
San Andreas	1.4 f	0.04 i	0.4 h	0.01 h	25 f	25 g
Albion	1.4 f	0.04 i	0.6 h	0.02 h	44 b-e	49 b-e
Seascape	1.0 f	0.02 i	0.4 h	0.01 h	36 ef	42 e
Chandler	1.0 f	0.02 i	0.2 h	0.01 h	13 g	17 g
Radiance	3.2 f	0.08 i	1.6 h	0.05 gh	48 bcd	57 bcd
Strawberry Festival	3.7 f	0.06 i	1.4 h	0.03 gh	38 de	47 def
Spring HT						
San Andreas	25.5 d	0.30 fg	12.6 f	0.18 de	49 b-e	58 a-e
Albion	18.7 e	0.22 h	7.5 g	0.10 fg	40 c-f	47 cef
Seascape	21.0 de	0.27 gh	9.9 fg	0.16 ef	46 b-e	56 b-e
Chandler	49.6 a	0.39 cde	22.9 bc	0.22 cde	46 b-e	56 b-e
Radiance	39.0 bc	0.48 ab	20.3 bcd	0.30 ab	51 a-e	61 abd
Strawberry Festival	39.2 b	0.36 def	17.4 de	0.21 de	44 b-e	57 a-e
Spring OF						
San Andreas	33.8 c	0.45 abc	18.4 cd	0.29 bc	54 bc	64 abc
Albion	22.1 de	0.33 efg	12.7 ef	0.21 de	58 ab	64 abc
Seascape	24.2 d	0.34 efg	13.9 ef	0.22 de	58 ab	64 abc
Chandler	44.1 b	0.42 bcd	23.0 b	0.25 bcd	51 b-e	59 bcde
Radiance	39.8 b	0.48 ab	22.0 bcd	0.31 b	56 abc	64 abc
Strawberry Festival	50.3 a	0.51 a	33.2 a	0.38 a	66 a	74 a
P value	*<.0001*	*0.0031*	*<.0001*	*0.0102*	*0.0010*	*0.0010*
$LSD_{(0.05)}$	5.4	0.08	5.0	0.08	15	16

[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).

Table 8. Production system irrigation/rainfall (mm) amounts during strawberry fruit ripening at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.			
Production system	**Irrigation (mm)**	**Rainfall (mm)**	**Total (mm)**
Winter HT	12.7	NA	12.7
Spring HT	25.4	NA	25.4
Spring OF	12.7	5.8	18.5
*Fruit ripening period: Winter HT, December 7-29; Spring HT, March 13-27; Spring OF, April 10-24.			

Table 9. Production system irrigation/rainfall (mm) amounts during strawberry fruit production at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.			
Production system	**Irrigation (mm)**	**Rainfall (mm)**	**Total (mm)**
Winter HT	88.9	NA	88.9
Spring HT	228.6	NA	228.6
Spring OF	101.6	156.5	258.1
*Fruit production period: Winter HT, December 2- January 12; Spring HT, March 2- June 14; Spring OF, April 6- June 29.			

Table 10. Influence of production system percent unmarketable yield of six cultivars of organically grown strawberry in high tunnel production 2011 and spring high tunnel and open field production 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.				
Production system	**Insect damage (%) (no./plant)**	**Insect damage (%) (kg/plant)**	**Gray mold (%) (no./plant)**	**Gray mold (%) (kg/plant)**
Winter HT	63 a	66 a	0 c	0 c
Spring HT	46 b	50 b	11 b	14 b
Spring OF	33 c	35 c	36 a	44 a
P value	*<.0001*	*<.0001*	*<.0001*	*<.0001*
$LSD_{(0.05)}$	8	9	6	5

[x] Numbers in the same column and main effect followed by the same letter are not significantly different according to Fisher's least significant difference test (α=0.05).
[y] Percent insect damage and percent gray mold were calculated from total unmarketable yield data (not presented).

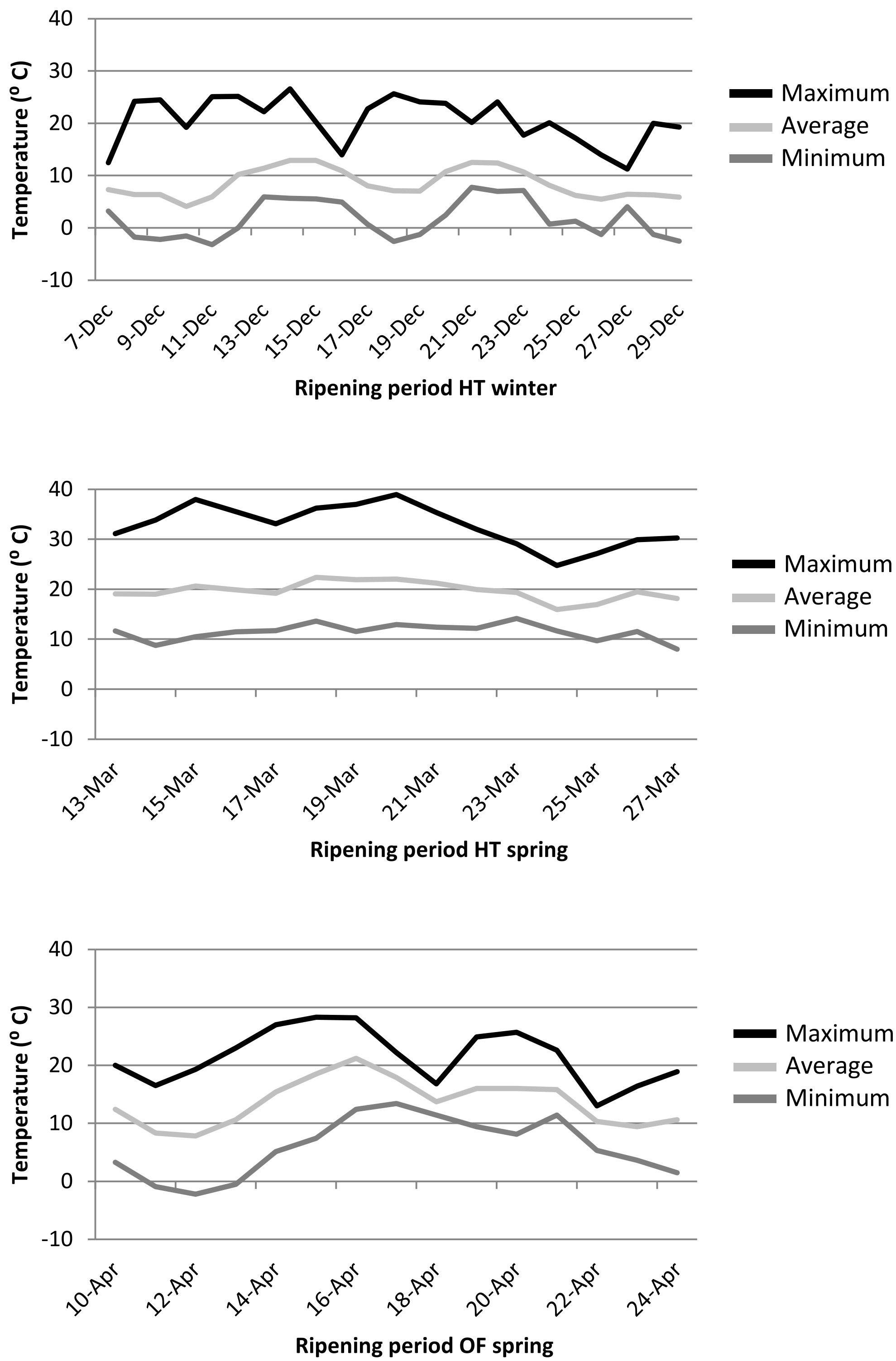


Figure 1. Daily maximum, average, and minimum temperatures (º C) during strawberry fruit ripening for HT winter, HT spring, and OF spring production seasons at the UT ETREC Organic Crops Unit in Knoxville, TN.

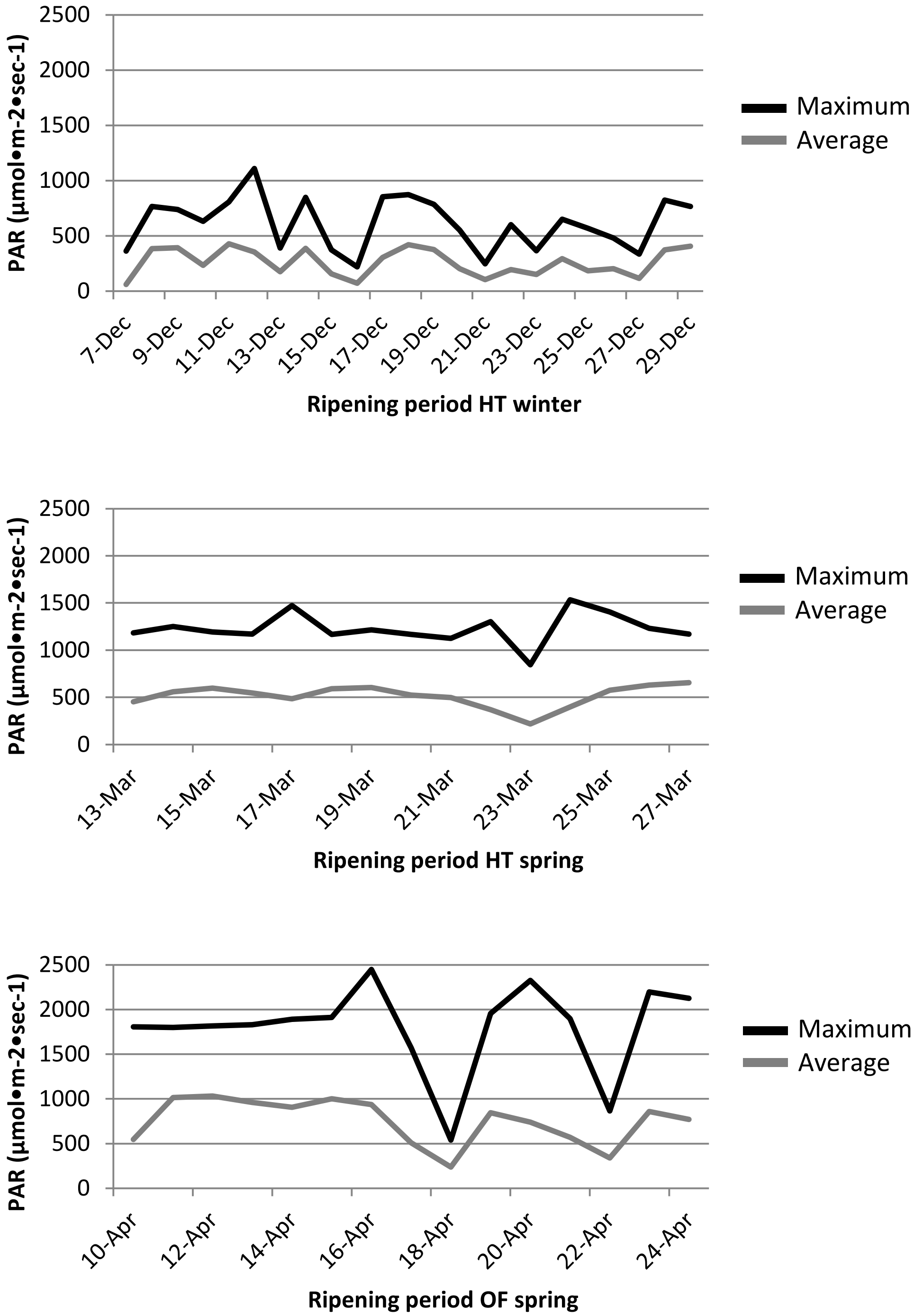


Figure 2. Daily maximum and average Photosynthetically Active Radiation (PAR) (µmol•m^2•sec-1) values during strawberry fruit ripening for HT winter, HT spring, and OF spring production seasons at the UT ETREC Organic Crops Unit in Knoxville, TN.

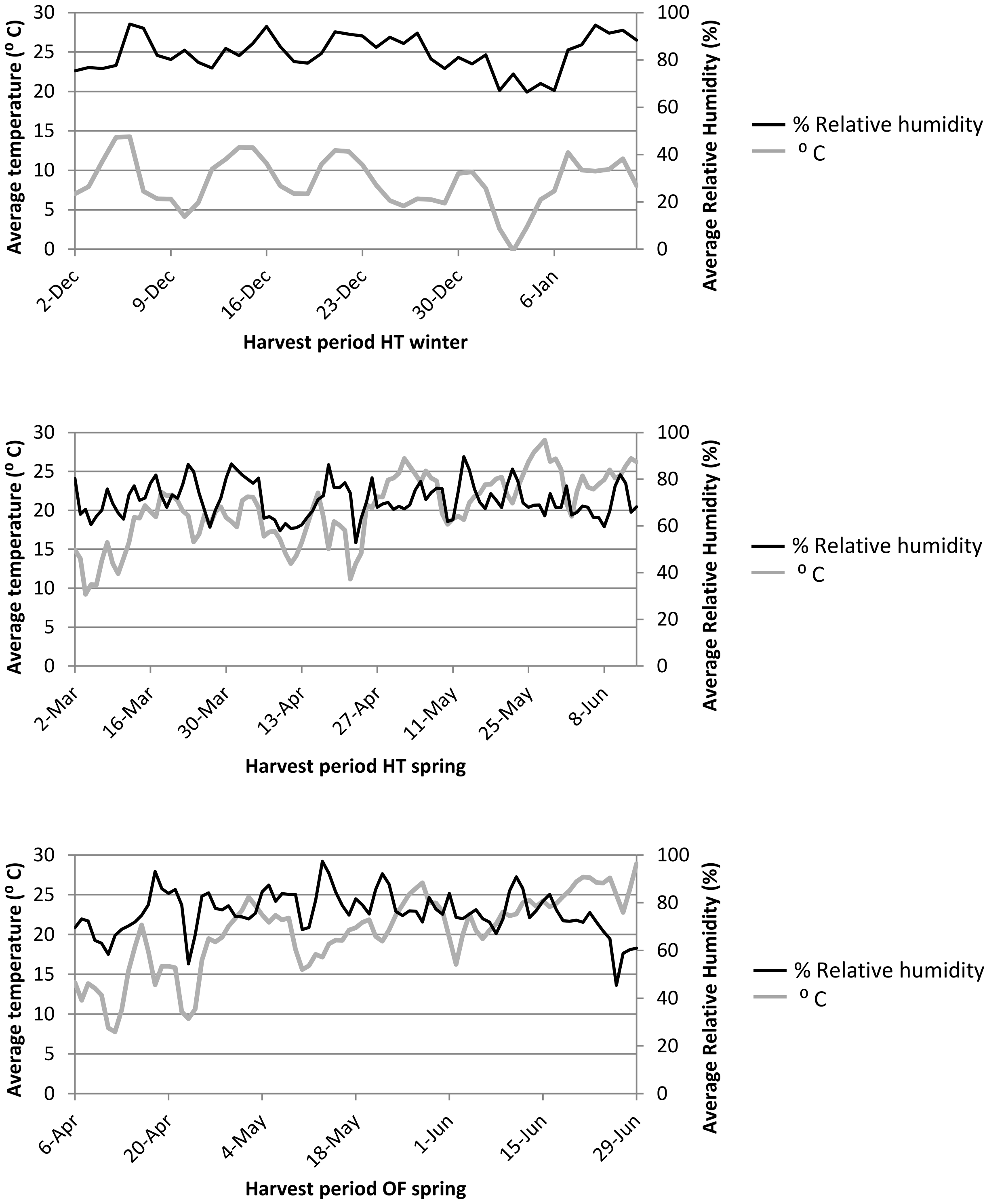


Figure 3. Daily average temperature (^{o} C) and daily average relative humidity (%) values during strawberry fruit harvesting for HT winter, HT spring, and OF spring production seasons at the UT ETREC Organic Crops Unit in Knoxville, TN.

Chapter 2:

Tomato (*Solanum lycopersicum)* Variety Comparison in Organically Managed High Tunnel and Open Field Production Systems

Abstract

High tunnel production has been increasing in the United States, as tunnels extend the growing season, increase marketability, and protect plants from weather events. Tomatoes (*Solanum lycopersicum*) are a high-value crop and high tunnel production can increase fruit quality, yield, and earliness of the season by a month in the spring and extend the season a month in the fall. Protection from low temperatures, rain, disease, and severe weather conditions help to minimize losses from environmental stressors. Tomato variety performance differs in the field, but differences have not been as well documented in high tunnel systems. The objective of this study was to determine the differences in yield and quality of four tomato cultivars grown in both high tunnel and open field production systems. This study showed an increase in total (182%) and marketable (214%) yield in the high tunnel system while extending the high tunnel season an average of 40 days compared to open field season.

Introduction

High tunnels are gaining popularity in the U.S., and in 2007 were present in 45 states with research ongoing in 36 states (Carey *et al.*, 2009). High tunnels are semi-permanent, passively heated structures with a plastic covering used to modify growing conditions, extend the production season, and protect crops from damaging weather events. High tunnels allow for nearly year round cultivation of vegetables, flowers, and small fruits (Lamont, 2009). In East Tennessee, cool season crops can be grown year-round, while the growing season for warm season crops can be extended by one month in both the spring (earlier) and fall (later).

Tomato (*Solanum lycopersicum*) is one of the commonly grown crops in high tunnels in the U.S. (Carey *et al.*, 2009; Knewtson *et al.*, 2010; USDA-ERS, 2010), and is able to increase revenue when compared with other crops (O'Connel *et al.*, 2012). Greater revenue is achieved from the early cash flow that high tunnels generate due to their ability to produce a crop up to one month earlier than the open field (O'Connel *et al.*, 2012), and as a result of the increased fruit quality achieved in the tunnel production system.

High tunnels increase fruit quality by protecting crops from low temperatures and overhead moisture, as well as severe weather conditions such as wind and hail (Lamont, 2009; O'Connel *et al*., 2012; Rogers and Wszelaki, 2012). Protection from rain allows for irrigation management and reduces disease incidence, thus improving crop quality and shelf life (Lamont, 2009). Early blight (*Alternaria solani*) of tomatoes is minimal in high tunnel production but is a serious foliage and fruit disease on open field tomatoes (Lamont, 2010). High tunnels reduce spore dispersal by preventing soil splash on plant leaves and reducing leaf wetness (Rogers and Wszelaki, 2012). The Southeast is conducive for tomato diseases due to warm temperatures and high humidity affecting plant performance. High tunnels limit the spread of disease as they reduce humidity and leaf wetness (Rogers and Wszelaki, 2012).

Severe rain and hail cause damage to foliage and fruit affecting yield and quality. High tunnels protect crops from wind which causes lodging of plants (Wien, 2009) affecting growth and production. Temperature also affects quality and allows for early, high quality production. The ability to plant and retain more heat earlier in the season causes an earlier accumulation of growing degree days which hastens plant growth and fruit production (Lamont, 2010).

Tomato variety trials have been studied in the past, but genetic differences may contribute to differences in high tunnel performance. In this study, seed sources changed for three of the four cultivars for one of three years, contributing to genetic differences. Furthermore, environmental conditions affect overall plant performance and conditions are modified in high tunnels. This study compares the yield and quality of four tomato cultivars (three hybrids and one heirloom) grown in both high tunnel and open field production systems for three years in the hot, humid Southeast.

Materials and Methods

This study was conducted in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN. The climate is subtropical with a hot and humid summer. The field elevation is 270 m, soil pH is 6.8, the average percent organic matter is 1.3%, and soil type is Dewey silt loam.

The experimental design was a completely randomized split plot with high tunnel (HT) and open field (OF) production systems as main-plots and tomato cultivars as sub-plots replicated four times. Four HTs (29.3 m long by 9.1 m wide) were erected at the site in spring 2010 (Golden Pacific Windjammer Series 5000; Golden Pacific Structures, Cincinnati, OH). The single-layer plastic covering on the HTs was Durafilm Super 4 (AT Films, Inc., Edmonton, Alberta, CA) with 92% optical transmission. The HTs were oriented North to South and located 3.2 m apart West to East. Four corresponding OF sites (29.3 m long by 9.1 m wide) were created to the East of the HTs located 3.4 m apart West to East and were oriented North to South.

Tomato cultivar sub-plots (4.3 m long by 0.6 m wide) included Early Girl, Celebrity, Cherokee Purple, and Red Defender (Table 11). Pre-plant organic fertilizer (Soybean Meal: 7.00 total N, 0.40 elemental P, 0.66 elemental K, Foothills Farmers Co-Op, Maryville, TN) was applied to deliver an estimated 33.63 kg N per hectare. The sub-plots were rototilled with a tiller (Kubota Tractor Corporation; model B7510; Torrance, CA). Drip irrigation (T-Tape, low flow, 16 mm diam., 8 mm, 30-cm emitter spacing, San Diego, CA) was laid in a single row in the center of each bed. In the HT and OF plots, standard agricultural polyethylene black plastic mulch (0.03 mm; Pliant Corp.; Schaumburg, IL) was laid by hand onto flat, pre-shaped beds on dates listed in Table 12. The mulch was laid by forming furrows at the edge of the bed with the mulch sides placed within the furrows. Soil was backfilled by hand to form a tight mulch layer on the bed surface. Transplant holes (10 cm diameter) were made with a WeedGuard Transplanter 0.6 m apart in a single row in each mulched bed with seven holes per sub-plot.

Tomato seedlings (6 to 9 weeks old) were transplanted on dates listed in Table 12. Tomato plants were pruned to one central leader, and staked using a Florida Weave training system (Kelbert *et al.*, 1966). In 2010, HT harvests began 15 June and ended 6 Aug (16 total), while the OF harvests began 7 July and ended 3 Aug (8 total). In 2011, HT harvests began 14 June and ended 22 Aug (18 total), while the OF harvests began 5 July and ended 22 Aug (15 total). In 2012, HT harvests began 5 June and ended 8 Aug (19 total), while the OF harvests began 10 July and ended 10 Aug (7 total).

Tomatoes were harvested at the "pink to red" stages of maturity following USDA maturity standards (7 CFR § 51.1904). Fruit were sorted into marketable and non-marketable categories. The number of fruit and total weight for marketable and for each unmarketable category was recorded. In 2010, all disorders were recorded for each fruit, accounting for greater than 100% unmarketable fruit. In subsequent years, the predominant disorder was recorded for each fruit. Primary disorders included fruit cracking, yellow shoulder, blossom end rot, and insect damage from Lepidopteron pests. The weights for each unmarketable category were divided by the total unmarketable weight to obtain percent unmarketable.

Water was applied via drip irrigation twice per week at 67 $m^{3} \cdot ha^{-1}$ (25.4 mm per row) per application in 2010 and twice per week at 33.5 $m^{3} \cdot ha^{-1}$ (12.7 mm per row) per application in 2011 and 2012 from transplanting until the end of the growing season, except when rainfall was adequate in the OF plots. Irrigation was applied to the OF plots when rainfall was not sufficient, and soil moisture was determined by touch-testing the soil to determine the amount of moisture in the top 7.62 cm of soil.

In 2010, plants were hand fertilized with Schafer's liquid fish fertilizer (2.00 total N, 0.40 elemental P, 0.17 elemental K) (Thomson, IL, U.S.) at 1.12 kg $N \cdot ha^{-1} \cdot day^{-1}$ every 15 days from 14 May to 15 July for a total of 5 applications. Plants were fertigated with 0.45 kg $N \cdot ha^{-1} \cdot day^{-1}$ every 7 to 10 days from 26 Apr to 11 Aug 2011 for a total of 15 applications in the HT plots and 13 applications in the OF plots, and from 13 Apr to 1 Aug 2012 for a total of 12 applications in the HT plots and 7 applications in the OF plots.

Insects and diseases were monitored weekly in the HT and OF plots via direct observation. Three plants were randomly chosen in each sub-plot and monitoring was limited to one minute or less per plant. Pest control products were applied as needed using a single-nozzle hand-held sprayer (SOLO 430-1G; Newport News, VA, U.S.). In 2010, prevention of late blight (*Phytophthora infestans*) was managed with four sprays of copper hydroxide (77% a.i. (Champ WG; Albaugh, Inc., Ankeny, IA)) at label rate of 1.98 kg per hectare a.i. on 4, 17 and 30 June, and 14 July. Black cutworms (*Agrotis ipsilon*) were managed with one application of silicon dioxide (77.69% a.i. (Diatomaceous Earth; Safer®, Woodstream Corporation, Lititz, PA)) applied as a light dusting over the plants on 1 Apr in the HT plots and 24 May in the OF plots. In 2011, green peach aphids (*Myzus persicae*) and potato aphids (*Macrosiphum euphorbiae*) were managed with one application of potassium salts of fatty acids (49 % a.i. (M-Pede; Gowan Company, Yuma, AZ)) at label rate of 0.03 ml per liter a.i. on 20 Apr, and with two applications of pyrethrins (1.4% a.i. (PyGanic Crop Protection EC; McLaughlin Gormley King Company, Minneapolis, MN)) at label rate of 15.68 ml per hectare a.i. on 19 and 27 May. The 19 May application of pyrethrins (1.4% a.i. (PyGanic Crop Protection EC)) was applied at 8x the label rate, 125.44 ml per hectare a.i., and caused chemical burn on tomato. One application of copper hydroxide (77% a.i. (Champ WG)) at label rate of 1.98 kg per hectare a.i. on 16 June was applied to prevent the onset of late blight. Damage from the tomato fruitworm (*Helicoverpa zea*), tomato hornworm (*Manduca quinquemaculata*), and true armyworm (*Pseudaletia unipuncta*) were managed with *Bacillus thuringiensis,* subsp. *Kurstaki,* strain ABTS-351 (54% a.i. (Dipel® DF; Valent BioSciences Corporation, Libertyville, IL)) at label rate of 0.60 kg per hectare a.i. on 21 July in the HT plots and 10 Aug in the OF plots. In 2012, damage from the tomato fruitworm, tomato hornworm, and armyworm were managed *Bacillus thuringiensis,* subsp. *Kurstaki,* strain ABTS-351 (54% a.i. (Dipel® DF)) at label rate of 0.60 kg per hectare a.i. on 11 June in the HT plots and 9 July in the OF plots.

Microclimate data were recorded with a Hobo U30-NRC weather station (Onset Computer, Bourne, MA, U.S.). Air temperature and photosynthetically active radiation (PAR) were recorded every 15 min from time of transplanting through final harvest. Due to the high costs of the weather monitoring equipment, only one HT replication and one OF replication were monitored, and were stationed in the second replication in each production system. Minimal variation among HT and OF replications likely existed due to their close proximity. In 2011, a severe hailstorm occurred 27 Apr severely damaging all four HT plastic covers. Plant damage was minimal and determined not to affect overall yields. The HT covers were replaced 31 May and 1 June. The replacement plastic covering for the HTs had the same specifications and was ordered from the same company (Durafilm Super 4; AT Films, Inc., Edmonton, Alberta, CA).

Statistical analyses. Statistical analyses compared main effects and interactions of cultivars (C), production system (PS), and year (Y). Data were analyzed as a completely randomized split-plot design. All data were subjected to analysis of variance (ANOVA) using PROC MIXED (SAS version 9.3; SAS Institute, Cary, NC). The Kenward-Rogers (1997) method was used to determine denominator degrees of freedom (DDFM) for F-tests in the analysis. All means were separated using Fisher's Least Significant Difference test (α = 0.05).

Results and Discussion

Main effects of production system, cultivar, and year affected tomato yield. When all three years were averaged together (Table 13), total and marketable yield (number and weight), and the percent of marketable yield was greater in the HT production system than the OF production system. Greater yields in the HT production system demonstrate the effect of HT production of fruit quality as HTs reduce damage from wind and injury from insects. Wittwer and Castilla (1995) found protected systems enable crops to have an indeterminate growth habit allowing for a longer harvest season when compared with field production.

In this study, the OF production system had a shorter season every year (44, 29, and 46 days, respectively). The OF season was shorter due to later plantings but also due to foliage loss from early blight (Rogers and Wszelaki, 2012). Each year early blight caused the OF plants to lose more than half of their leaves by the second week in July (Data not shown). Flower production was not able to continue which reduced the number of total fruit produced. Cultivars did not demonstrate resistance over one another in regards to early blight infection, and the harvested fruit did not display damage from early blight.

The type of growth habit influences the length of harvest and the amount of fruit produced. Determinate varieties (cvs. Celebrity and Red Defender) bear their crop within a defined time frame (4 to 6 weeks), while indeterminate varieties (cvs. Cherokee Purple and Early Girl) produce new vegetative growth and fruit throughout the season (Jett, 2010). Hybrid tomatoes are bred for their production and resistance to specific diseases (i.e. vertical resistance) but were as susceptible in this study as the heirloom cultivar. Hybrid tomato fruit is consistent in shape and size and resists cracking and bruising. Heirloom tomatoes resemble their parent and are known for their outstanding flavor. Heirlooms can be challenging as they are inconsistent in growth and are susceptible to cracking and bruising (Vavrina *et al.*, 1997). Cherokee Purple was the only heirloom and indeterminate variety in this study and had some of the lowest yields. Early Girl was the only hybrid, indeterminate variety and achieved some of the highest total and marketable yields. Celebrity and Red Defender (hybrid and determinate) had yields between that of Cherokee Purple and Early Girl.

When all three years were averaged together, total and marketable yield (number and weight) were greater for the cultivar Early Girl than all other cultivars (Table 13), except Celebrity regarding total fruit weight and Red Defender regarding marketable fruit weight. Cherokee Purple had the lowest total and marketable yield (number and weight) compared to all cultivars, except for Celebrity regarding marketable fruit weight. Celebrity and Cherokee Purple had the lowest marketable yield (number and weight) compared to all other cultivars. The hybrids Early Girl and Red Defender had greater percent marketable yield and is reflected in the marketable yield (number and weight). Cherokee Purple and Red Defender had higher marketable weight per fruit and these cultivars are noted to be of larger size. Overall, the three hybrid cultivars out-yielded the heirloom cultivar in each category except average fruit weight.

Cherokee Purple consistently performed poorly concerning total and marketable fruit number and weight in the OF (Table 13). Poor performance of heirloom varieties is attributed to thinner skin, lack of uniformity, and lower yields compared to hybrid or commercial varieties (Rivard and Louws, 2008). Although heirloom production is lower than hybrid production, heirlooms have been increasing in popularity and consumer demand over the last 20 years in fresh markets (Jordan, 2007). HTs allow higher quality production than the OF as Cherokee Purple had three-times more marketable fruit (number and weight) in the HT production system versus the OF (Table 13). However, Cherokee Purple still had significantly lower yields than the other cultivars. Growers are able to achieve price premiums of 15 to 20% with organic heirloom tomatoes compared to conventional tomatoes (Fernandez-Cornejo *et al*., 1994; Stevens-Garmon *et al*., 2007) and these higher prices can offset differences in yield.

In 2010 and 2011, the Y *x* C interaction (Table 13) showed the cultivar Early Girl had greater total and marketable yields (number and weight) than all other cultivars except Celebrity in regards to total weight. In 2012, Early Girl had greater total and marketable number of fruit; however, total fruit weight was lowest in 2012, and the average marketable weight per fruit was lowest for Early Girl each year. Although Early Girl produced the most fruit, they were consistently smaller fruit compared to the other cultivars in 2011 and 2012. Early Girl is described as having medium fruit, but in our study the fruit were smaller than the other cultivars. In 2010 and 2011, Cherokee Purple had the lowest total and marketable yields (number and weight), while in 2012 Cherokee Purple had greater marketable fruit weight than Celebrity. However, in 2011 and 2012 the average marketable weight per fruit was greatest for Cherokee Purple compared to all other cultivars. Although Cherokee Purple did not produce high numbers of fruit, the fruit that were produced were larger and of greater weight, which is in agreement with descriptions of Cherokee Purple's fruit. The greatest percent marketable yield was attained in 2011 for all cultivars, ranging from 38-64% marketable, while 2012 marketability ranged from 12-35% and 2010 showed the lowest percentage of marketable fruit, ranging from 1.3% for Cherokee Purple and 27.7% for Red Defender. The difference in cultivar performance may be due to different sources for seed. Different seed sources have been found to alter the phenotypic traits of a crop causing inconsistent yields and growth (Ginwal *et al.*, 2004). Phenotypic variation from different seed sources may have contributed to yield differences but environmental factors also determined crop performance.

Yield differences across years are attributed to heat stress affecting pollen release and germination and inconsistent irrigation amounts (Sato *et al.*, 2000). In 2010 and 2011, HT temperatures were more conducive for fruit development (Fig. 4), but irrigation amounts were too high in 2010 causing more fruit to crack. In 2012, HT temperatures were elevated throughout fruit development contributing to less marketable fruit. Peet (2005) found that tomato blossoms drop after enduring four hours of temperatures at or above 40 ^{o}C. This temperature extreme occurred in the 2012 HT between 14 June and 8 Aug for a total of 50 hours (Fig. 4). However, in the 2010 and 2011 HTs, 40 ^{o}C was reached only briefly (< 1 hour). In the 2012 OF, temperatures reached levels at or above 40 ^{o}C totaling 6 hours (Fig. 4) and occurred between 30 June and 1 July. However, this temperature extreme was not reached in 2010 or 2011 OF.

The PS *x* Y interaction (Table 13) showed marketable yield (number and weight) was greater in the HT in 2011 than all other PS *x* Y interactions, while the OF for both 2010 and 2012 had lower marketable yields than all HT plots and years. In 2011, the OF plots performed comparably to the HT plots from 2010 and 2012, indicating that 2011 yields were higher than the other two years regardless of production system. The percent marketable yield was greater in both the HT and OF in 2011 than all other PS *x* Y combinations, while 2010 OF had the lowest percent marketable yield. The percent marketable yield did not differ between production systems in 2011 and 2012. The percent marketable yield only differed among the production systems in 2010. The 2010 HT system had a higher percentage of marketable yield compared to the 2010 OF system due to the combination of irrigation and rainfall causing more fruit to split and crack in the OF. A study by O'Connel *et al.* (2012) found marketable fruit weight was 55% greater in the HT system which is in agreement with our findings from 2010.

Only in the 2012 OF were the marketable weight per fruit greater than all other PS *x* Y combinations. In the 2012 OF, fewer marketable fruit were able to grow to large sizes without cracking from excess moisture. These few, large marketable fruit increased the ratio of weight per fruit compared to all other PS *x* Y interactions.

Each year yields were below the 11 kg plant optimum for HT production (Table 13) (Jett, 2010). Low yields have been found to be a result of low soil N availability (Scow *et al.*, 1994), which is a challenge with low soil organic matter (1.3%) and during transition to organic production (Rogers and Wszelaki, 2012). While this study was managed organically, prior to the study the field had been in conventional small grain production for 35 years. Rogers and Wszelaki (2012) found a decrease in tomato yield during the transition to organic production due to the lack of biomass and soil organic matter.

Low yields in 2012 were a result of low N and deficient irrigation, which has been found to decrease the number and weight of fruit (Pulupol *et al.*, 1996). Low marketable yields in 2010 were a result of low N and excess irrigation, which has been found to cause fruit to split prior to harvest. Due to the high occurrence of growth cracks in 2010, irrigation amounts were reduced by half and applied twice per week in 2011 and 2012. The four most common causes of unmarketable fruit varied between the HT and OF production systems and cultivars (Tables 4 and 5).

Growth cracks occurred more often in the OF contributing to 35.8-100% of unmarketable fruit each year (Table 14). Growth cracks were greater, on average, for the cultivars Celebrity (41.3-94%) and

Cherokee Purple (40.6-99.3%) in 2010 and 2011, and Cherokee Purple (38.9%) in 2012 (Table 15). Cherokee Purple has a thin skin and is more likely to develop cracks. A study by Sperry *et al.* (1996) found the cultivar Celebrity to be susceptible to cracking as a genetic trait. Rainfall amounts in the open field are often unpredictable contributing to more cracking as a result of excess water in the fruit. A study by Rogers and Wszelaki (2012) found OF tomatoes that are vine-ripened have a greater likelihood to crack and split due to excess irrigation.

In 2010, nearly 40% of the unmarketable fruit was a result of cracking in the HT system (Table 14). Decreasing the irrigation amount in 2011 and 2012 lessened the occurrence of growth cracks in the HT system (18.7 and 11.3%, respectively). Due to rain, the OF system still had a higher percentage of cracks each year compared to the HT system. A study by Emmons and Scott (1997) showed direct exposure to sunlight also can cause tomato fruit to crack and direct sunlight is reduced in HTs due to the plastic's UV light-absorbing components (Costa *et al.*, 2002). However, the OF plants were exposed to direct sunlight and did not produce as much foliage to protect the fruit from sunlight as the HT, thereby contributing to the larger percent cracking in the OF.

Yellow shoulder affected a large portion of unmarketable fruit each year in both production systems, but in 2011 caused more than twice as many unmarketable fruit in the HT compared to the OF (Table 14). Previous studies found potassium uptake to increase during fruiting and is important in regards to fruit pigmentation (Huett and Dettman, 1988; Hartz *et al.*, 2005). Yellow shoulder causes fruit to have large amounts of internal white tissue as a result of low potassium (Madakadze and Kwaramba, 2004). Soils that undergo intense cropping practices can cause the available potassium to become exhausted in the soil, and soils with low organic matter (<1.5%) are at higher risk (McIntyre, 2004). If potassium is not available for plant uptake then tomatoes are more susceptible to yellow shoulder.

High temperatures (>33 ^{o}C) have been found to be a contributing factor in the incidence of yellow shoulder as water is not taken up as easily (S. Bogash personal communication). High temperatures and low soil organic matter (<1.5%) help to explain why yellow shoulder occurred in both production systems. The HT production system had a higher incidence of yellow shoulder as a result of its prolonged exposure to high temperatures (>33 ^{o}C) compared to the OF production system (Fig. 4). Previous studies have found yellow shoulder to be linked to a genetic component and some cultivars require higher amounts of potassium (Corey *et al.*, 1986; Hartz *et al.*, 1999). In this study, yellow shoulder affected a large portion of unmarketable fruit on the cultivars Celebrity (22.3-48.1%) and Early Girl (26.5-44.5%); however, Cherokee Purple was least affected (0.2 to 4.6%) which suggests Cherokee Purple may have a lower potassium requirement (Table 15).

Blossom end rot occurred at least four-times more often in the HT production system versus the OF each year (Table 14). By the third year, nearly 30% of unmarketable fruit in the HT were a result of blossom end rot. A main cause of blossom end rot results from the inability of a plant to uptake calcium (Dorais and Papadopoulos, 2001; Hunter *et al.*, 2010). The inability to uptake calcium was a result of uneven levels of available moisture due to scheduled irrigation. The HTs were irrigated the same in 2011 and 2012, but maximum air temperatures in 2011 were lower than the 2012 HT temperatures (mentioned above) causing water stress and increased evapotranspiration in 2012. Irrigation levels were not increased to account for the greater rate of evapotranspiration in 2012 causing a higher incidence of blossom end rot. Unmarketability due to blossom end rot was minimal (≤ 1.4%) in the OF as moisture levels were supplemented with overhead rainfall (Fig. 5) in addition to irrigation.

Both water stress and cultivar susceptibility have been found to cause blossom end rot (Shaykewich *et al.,* 1971). In 2010 and 2012, blossom end rot occurred more often for the cultivar Red Defender (6.1 and 17.6%), except in 2012 when Early Girl (22.0%) reached similar levels (Table 15). Blossom end rot occurred more often in 2012 and shows that water stress initiates the disorder but genetics contribute to the severity.

In 2011, Early Girl and Red Defender showed greater levels of insect damage, while in 2012 Cherokee Purple and Red Defender showed greater levels of insect damage (Table 15). Damage from insects varied among cultivars as plants' defensive chemistry is varied between genotypes and individual plants within a population (Strauss, 1991). Pests established after the 2010 season and were able to navigate more efficiently in the OF than the HT due to the reduction of UV-light as a result of the HT plastic cover. Insect damage was greater in the OF in 2011 (36.6%) and 2012 (30.4%) and did not exceed 11% in the HT each year (Table 14). High tunnel plastic coverings contain UV light-absorbing components that help to reduce the amount of UV radiation (Costa *et al.*, 2002). Diaz *et al.* (2006) found UV blocking plastic films to reduce lepidopteran pests and this order of insect was the primary cause of damage in our study. Reduced pest pressure resulted from interference with behavioral responses to UV light (Antignus *et al.*, 1996). Lepidopteran pests were not able to establish or navigate as effectively in the HT as in the OF due to the UV interference caused by the HT plastic covering.

The HT system consistently achieved greater total, marketable, and percent marketable yields than the OF system each year (Table 13). In 2011, both production systems produced more marketable fruit when compared to 2010 and 2012. In 2011, irrigation amounts were adequate and this demonstrates how important irrigation management is in a HT system. The cultivar Early Girl consistently had greater total and marketable yields than all other cultivars each year (Table 13) and in each production system (Table 13). The HT production system more than doubled marketable yields for all cultivars except Red Defender (Table 13). Although HT allows for more control over the climate, it is not always possible to maintain ideal temperatures for fruit development inside the tunnel. Close attention should be paid to variety selection, irrigation, plant nutrition, and soil organic matter, as these factors determine the quality of tomato fruit.

Appendix: Chapter 2

Table 11. Tomato cultivars evaluated in HT and OF tomato culture in 2010, 2011, and 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

Solanum lycopersicum Cultivar	Description	Seed Source
Early Girl	F1 Hybrid; indeterminate; medium to large; 65 days to maturity	2010/2011: Territorial Seed Company 2012: Park Seed Company
Celebrity	F1 Hybrid; determinate; medium to large; 72 days to maturity	2010: Territorial Seed Company 2011/2012: Harris Seeds
Cherokee Purple	Heirloom; indeterminate; large to extra-large; 72 days to maturity	2010: SeedWay 2011/2012: Johnny's Selected Seeds
Red Defender	F1 Hybrid; determinate; large to extra-large; 75 days to maturity	2010/2011/2012: Harris Moran Seed Company

Table 12. Growing environment characteristics in high tunnels (HT) and the open field (OF) in 2010z, 2011, and 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN

	2010[z]		2011		2012	
	HT	OF	HT	OF	HT	OF
Tomato planting	25 Mar	5 May	7 Apr	6 May	28 Mar	15 May
First harvest	15 Jun	7 Jul	14 Jun	5 Jul	5 Jun	10 Jul
Last harvest	6 Aug	3 Aug	22 Aug	22 Aug	8 Aug	10 Aug
No. of harvests	16	8	18	15	19	7
GDD[yw] (base 10 °C)	1876	1434	2204	1707	2118	1342
Ave. daily max. air temp.[w] (°C)	34.0	33.4	34.7	33.2	35.6	32.8
PAR[xw] ($\mu mol \cdot m^2 \cdot sec-^1$)	626	852	581	783	594	865
Total rainfall[w] (mm)	0	207	0	270	0	251

[z] In 2010, data collected in the HT from 9 Apr. until 6 Aug. due to sensor malfunction, and 6 May until 3 Aug. in the OF. Missing data prior to malfunction not included.
[y] Growing degree days calculated base 10° C as [(Tmax+Tmin/2)-10], with negative daily degree days converted to zero.
[x] PAR is photosynthetically active radiation ($umol \cdot m^2 \cdot sec^{-1}$) for the period of time plants were grown.
[w] GDD, average daily maximum air temperature, PAR, and total rainfall were based on the period of time plants were grown.

Table 13. Influence of cultivar and production system x cultivar interaction on tomato yield per plant at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN in 2010, 2011, and 2012.						
	Total yield[vu] (no./plant)	Total yield[yv] (kg/plant)	Marketable yield[xv] (no./plant)	Marketable yield[yvt] (kg/plant)	% Marketable yield (kg/plant)	Average marketable weight per fruit[w] (kg)
Production system						
High tunnel	45.3 a	7.00 a	15.1 a	2.42 a	34.7 a	0.20
Open field	17.9 b	3.84 b	5.6 b	1.13 b	28.0 b	0.23
P value	*<0.0001*	*0.0003*	*<0.0001*	*<0.0001*	*0.0090*	*0.0764*
$LSD_{(0.05)}$	4.7	1.05	1.8	0.33	4.9	0.03
Cultivar						
Celebrity	31.5 b	6.17 a	6.6 c	1.37 b	20.3 b	0.22 b
Cherokee Purple	15.4 d	4.35 c	3.8 d	1.07 b	24.4 b	0.28 a
Early Girl	53.8 a	5.73 ab	21.5 a	2.55 a	41.5 a	0.13 c
Red Defender	25.9 c	5.44 b	9.4 b	2.10 a	39.2 a	0.24 ab
P value	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
$LSD_{(0.05)}$	3.2	0.59	2.6	0.46	7.0	0.04
Year						
2010	31.3	5.34	6.6 b	1.07 c	16.4 c	0.18 c
2011	33.7	5.54	16.5 a	2.80 a	49.1 a	0.21 b
2012	29.9	5.59	7.9 b	1.61 b	28.6 b	0.26 a
P value	0.4076	0.7032	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
$LSD_{(0.05)}$	5.6	0.63	3.4	0.49	5.8	0.03
Ps x c						
High tunnel						
Celebrity	44.3 b	8.12 a	10.1 b	2.01 bc	24.7	0.21
Cherokee Purple	21.2 de	5.31 c	5.8 cd	1.51 c	30.1	0.28
Early Girl	82.9 a	7.94 a	33.7 a	3.67 a	45.7	0.11
Red Defender	32.9 c	6.64 b	10.9 b	2.50 b	38.2	0.23
Open Field						
Celebrity	18.7 e	4.22 cd	3.2 de	0.73 d	16.0	0.23
Cherokee Purple	9.6 f	3.38 e	1.8 e	0.64 d	18.6	0.29
Early Girl	24.6 d	3.52 de	9.3 bc	1.43 c	37.3	0.16
Red Defender	18.8 e	4.24 cd	7.9 bc	1.71 c	40.2	0.25
P value	*<0.0001*	*0.0001*	*<0.0001*	*0.0097*	*0.2425*	*0.8454*
$LSD_{(0.05)}$	5.2	1.04	3.6	0.66	9.9	0.06

Table 13. Continued						
	Total yield[vu] (no./plant)	Total yield[yv] (kg/plant)	Marketable yield[xv] (no./plant)	Marketable yield[yvt] (kg/plant)	% Marketable yield (kg/plant)	Average marketable weight per fruit[w] (kg)
Ps x y						
High tunnel						
2010	44.3 a	6.84 a	11.7 b	1.84 b	25.5 b	0.18 b
2011	45.4 a	6.93 a	21.3 a	3.49 a	49.0 a	0.21 b
2012	46.3 a	7.65 a	12.3 b	2.25 b	29.5 b	0.22 b
OpenfField						
2010	18.2 bc	3.84 b	1.5 c	0.31 c	7.3 c	0.17 b
2011	22.0 b	4.15 b	11.7 b	2.11 b	49.2 a	0.21 b
2012	13.6 c	3.53 b	3.5 c	0.96 c	27.6 b	0.31 a
P value	*<0.0001*	*0.0456*	*0.0020*	0.0034	*0.0036*	*0.0123*
$LSD_{(0.05)}$	7.9	1.06	4.8	0.69	8.2	0.05
Year x cultivar						
2010						
Celebrity	30.5 c	5.86 ab	4.3 de	0.75 fg	10.9 d	0.18 efg
Cherokee Purple	14.1 e	4.15 de	0.23 e	0.06 g	1.3 d	0.16 fg
Early Girl	56.0 ab	5.87 ab	15.3 b	1.92 cd	25.8 c	0.13 g
Red Defender	24.4 cde	5.48 bc	6.6 cd	1.58 de	27.7 bc	0.24 b
2011						
Celebrity	34.2 c	6.40 ab	12.4 bc	2.54 bc	38.0 b	0.21 def
Cherokee Purple	13.5 e	3.85 e	5.0 de	1.59 de	39.0 b	0.31 ab
Early Girl	59.5 a	6.65 a	34.3 a	4.19 a	63.6 a	0.13 g
Red Defender	27.5 cd	5.26 bcd	14.2 b	2.86 b	55.7 a	0.21 def
2012						
Celebrity	29.9 c	6.25 ab	3.2 de	0.82 efg	12.1 d	0.26 bcd
Cherokee Purple	18.4 de	5.87 ab	6.3 de	2.20 bcd	32.8 bc	0.37 a
Early Girl	45.8 b	4.66 cde	14.8 b	1.54 def	35.2 bc	0.14 g
Red Defender	25.6 cd	5.59 abc	7.4 cd	1.87 cd	34.2 bc	0.27 bc
P value	*0.0105*	*0.0007*	*0.0006*	*<0.0001*	*0.0074*	*<0.0001*
$LSD_{(0.05)}$	11.2	1.15	6.0	0.83	11.4	0.06

Table 13. Continued
[z]Means within a column followed by the same letter are not significantly different (*P*=0.05) as determined by Fisher's protected least significant difference (LSD) test. [y] Ps, c, and Ps x c; In 2012, an outlier was removed to achieve normality; HT Cherokee purple [x] Ps, c, and Ps x c ; In 2011, an outlier was removed to achieve normality; HT Early girl [w] Ps, c, and Ps x c; In 2012, an outlier was removed to achieve normality; HT Celebrity [v] Ps x y; Total yield and marketable yield data were $\log_{10}$ transformed to achieve normality; data presented is non-transformed means. [u] Y x c; Total yield (no./plant) was $\log_{10}$ transformed to achieve normality; data presented is non-transformed means. [t] Y x c; In 2012, an outlier was removed to achieve normality; HT Cherokee Purple

Table 14. Influence of production system (HT and OF) on percentage of unmarketable tomato fruit per plant in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

	Growth cracks[x] (%)	Yellow shoulder (%)	Blossom end rot[w] (%)	Insect amage (%)
2010[y]				
High tunnel	39.8 b	36.8	6.1 a	5.0
Open field	100.0 a	21.7	1.4 b	6.9
P value	*<.0001*	*0.0541*	0.0026	*0.5300*
$LSD_{(0.05)}$	9.6	15.8	2.2	8.0
2011				
High tunnel	18.7 b	22.1 a	6.5 a	8.7 b
Open field	35.8 a	9.9 b	1.0 b	36.6 a
P value	*0.0004*	*<.0001*	*<.0001*	*<.0001*
$LSD_{(0.05)}$	*8.6 8.5*	*4.5*	2.0	6.5
2012				
High tunnel	11.3 b	35.7	30.1 a	10.3 b
Open field	36.2 a	20.7	0.4 b	30.4 a
P value	*<.0001*	*0.1067*	*0.0185*	*<.0001*
$LSD_{(0.05)}$	5.7	19.4	22.7	5.7

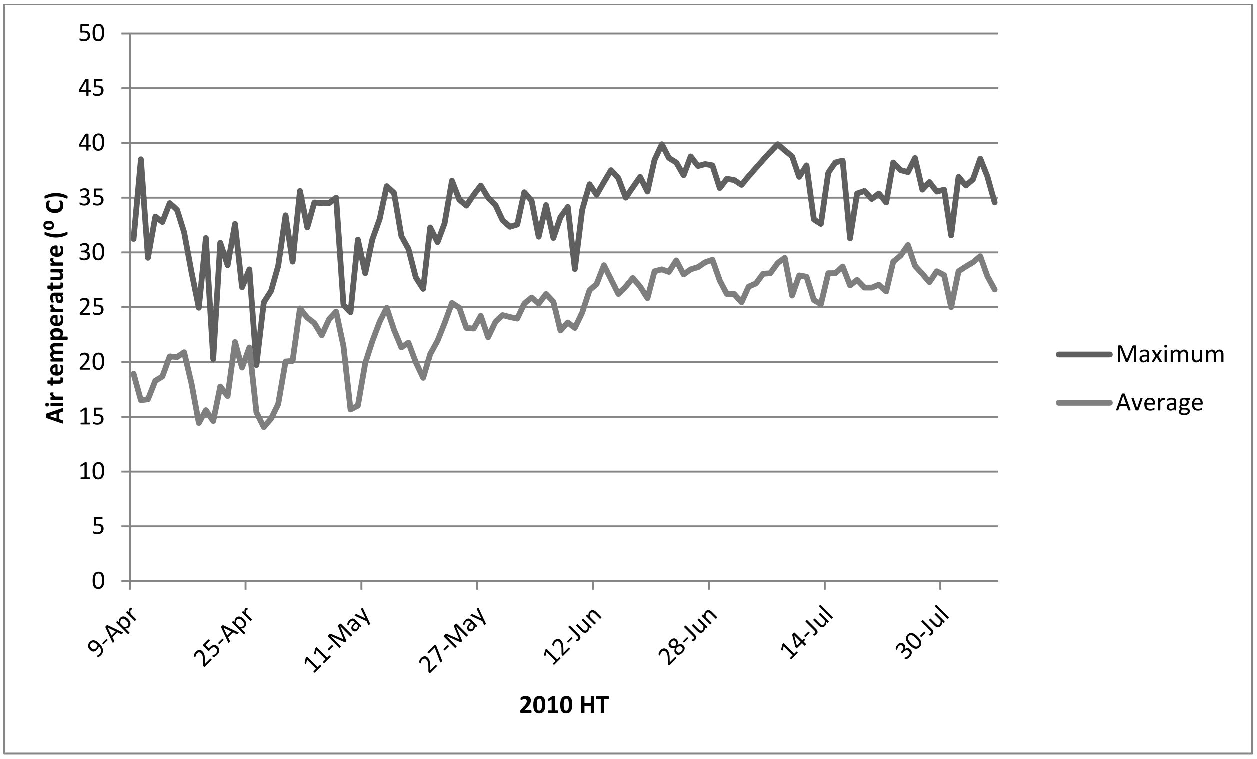
[z]Means within a column followed by the same letter are not significantly different (*P*=0.05) as determined by Fisher's protected least significant difference (LSD) test.
[y] In 2010, if more than one disorder occurred on a fruit, all disorders were accounted for totaling more than 100%.
[x] In 2011, an outlier was removed to achieve normality; HT Cherokee purple
[w] In 2010, an outlier was removed to achieve normality; HT Early girl

Table 15. Influence of year on percentage of unmarketable fruit per plant in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

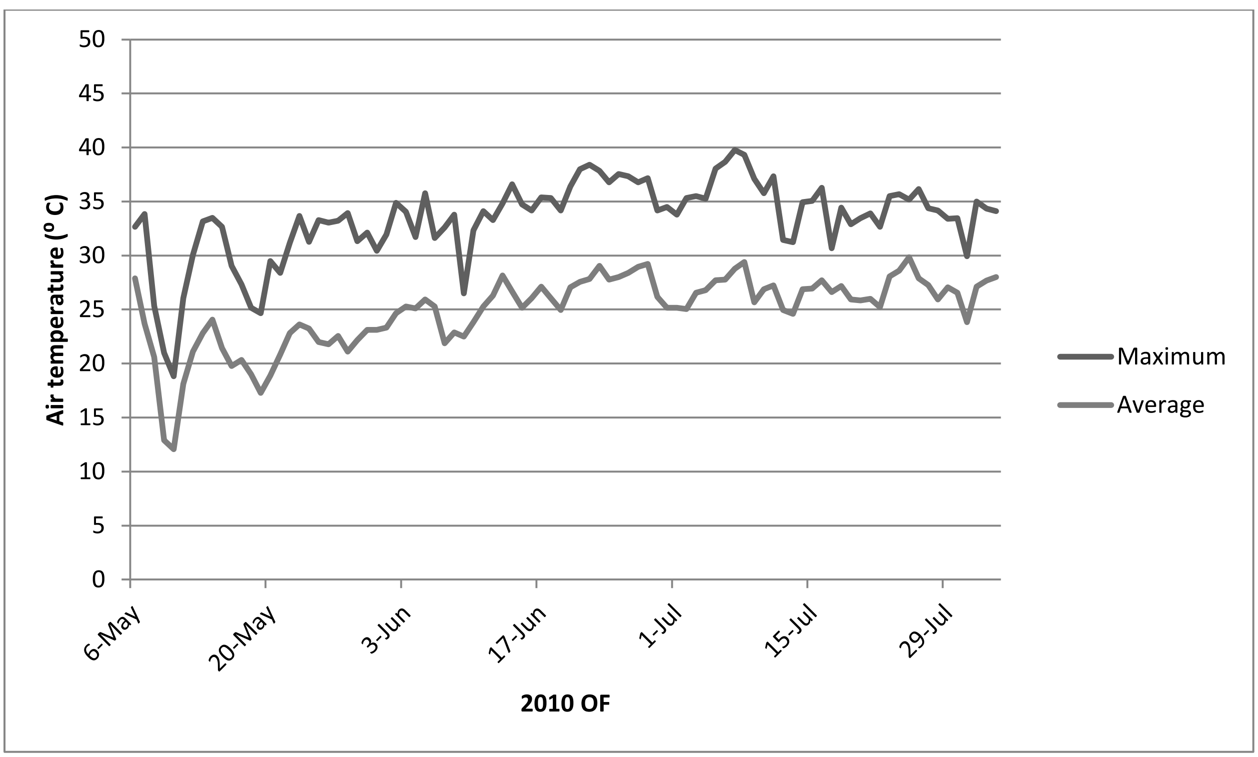
Year	Growth cracks[x] (%)	Yellow shoulder (%)	Blossom end rot[w] (%)	Insect damage (%)
2010[y]				
Celebrity	94.0 a	48.1 a	3.3 b	5.0
Cherokee Purple	99.3 a	3.4 c	2.4 b	6.5
Early Girl	44.7 b	38.1 ab	3.2 b	4.4
Red Defender	51.2 b	27.4 b	6.1 a	7.9
P value	*<.0001*	*<.0001*	0.0343	0.3873
$LSD_{(0.05)}$	13.9	13.8	2.6	4.7
2011				
Celebrity	41.3 a	22.3 a	3.8	15.5 c
Cherokee Purple	40.6 a	4.6 b	3.3	17.6 bc
Early Girl	6.1 b	26.5 a	2.3	31.5 a
Red Defender	15.6 b	10.7 b	5.7	25.9 ab
P value	*<.0001*	*<.0001*	*0.1324*	*0.0052*
$LSD_{(0.05)}$	*10.0*	*6.4*	2.9	9.3
2012				
Celebrity	20.4 c	43.1 a	12.4 b	10.3 c
Cherokee Purple	38.9 a	0.2 c	9.0 b	31.2 a
Early Girl	9.7 d	44.5 a	22.0 a	16.2 bc
Red Defender	26.0 b	25.0 b	17.6 ab	23.6 ab
P value	*<.0001*	*<.0001*	*0.0332*	*0.0001*
$LSD_{(0.05)}$	5.1	11.0	8.9	8.0

[z]Means within a column followed by the same letter are not significantly different (*P*=0.05) as determined by Fisher's protected least significant difference (LSD) test.
[y] If more than one disorder occurred on a fruit, all disorders were accounted for totaling more than 100%.
[x] In 2011, an outlier was removed to achieve normality; HT Cherokee Purple
[w] In 2010, an outlier was removed to achieve normality; HT Early Girl

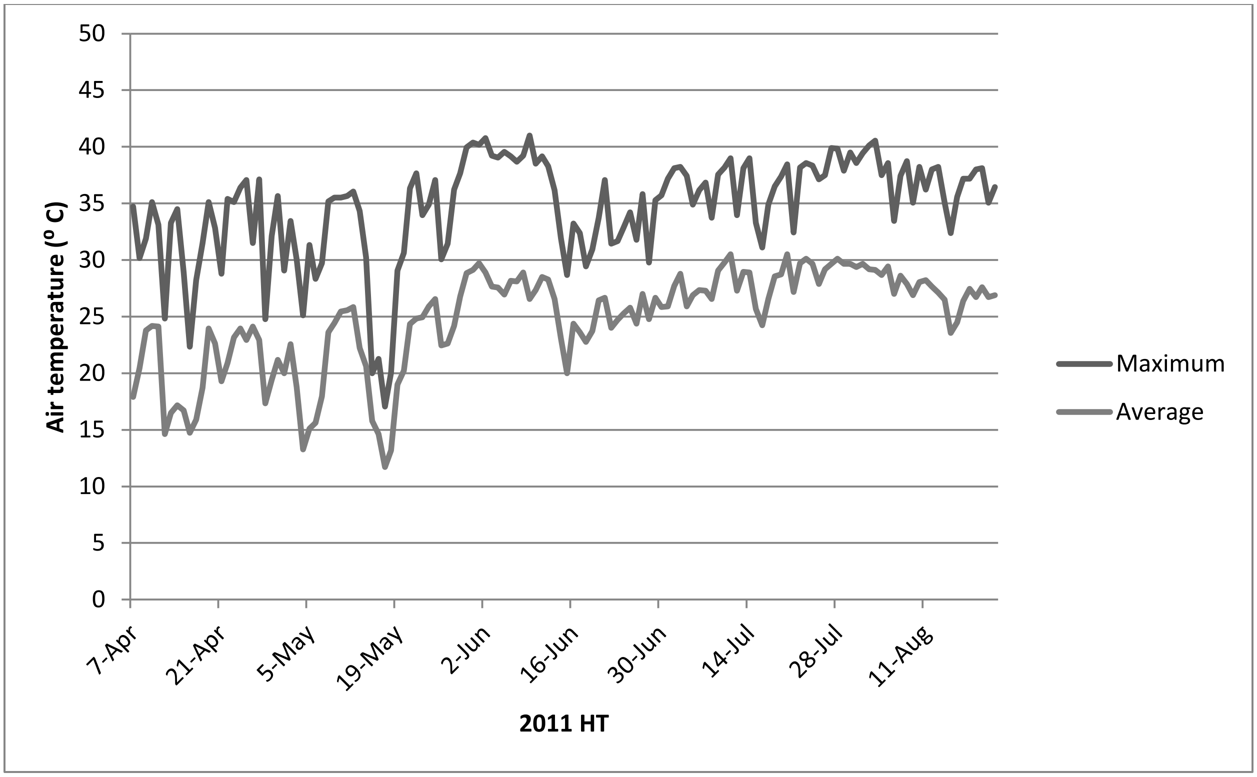
Figure 4. Daily maximum and average air temperature (^{0} C) for 2010, 2011, and 2012 during the time tomatoes were grown in the high tunnel (HT) and the open field (OF) plots at the UT ETREC Organic Crops Unit in Knoxville, TN.



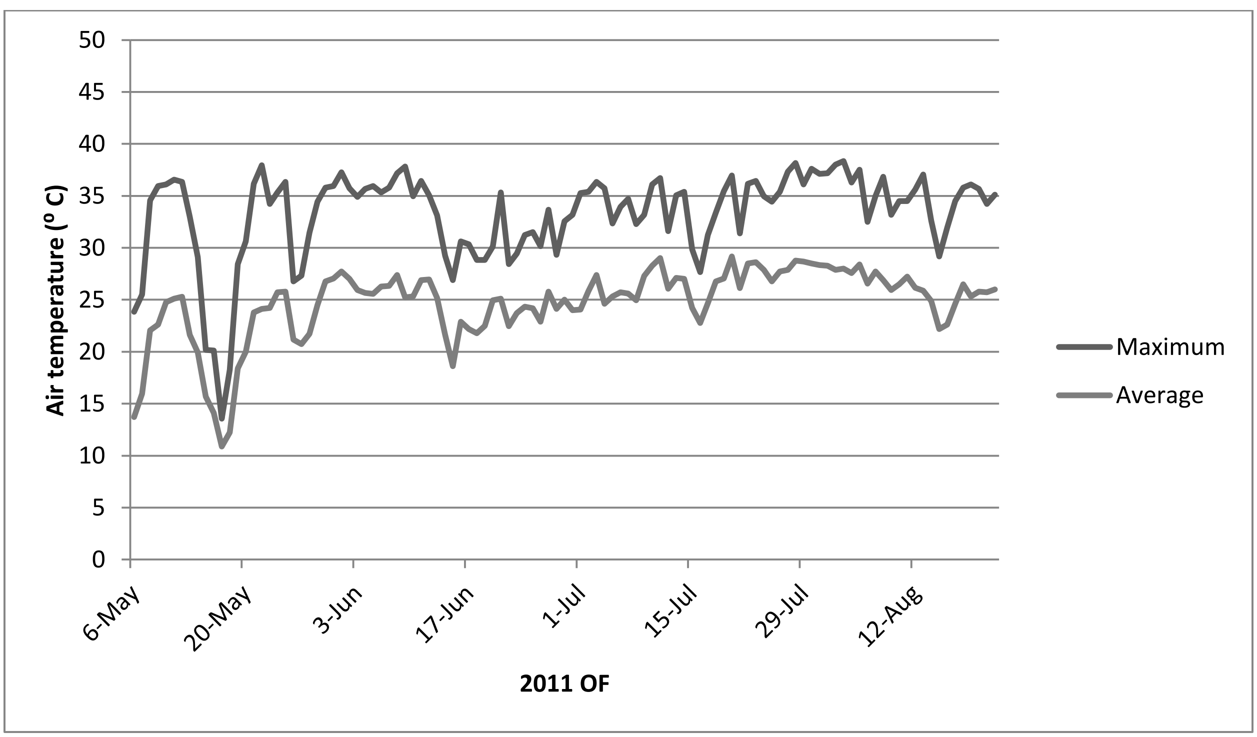
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
9-Apr
25-Apr
11-May
27-May
12-Jun
28-Jun
14-Jul
30-Jul
2010 HT
Maximum
Average



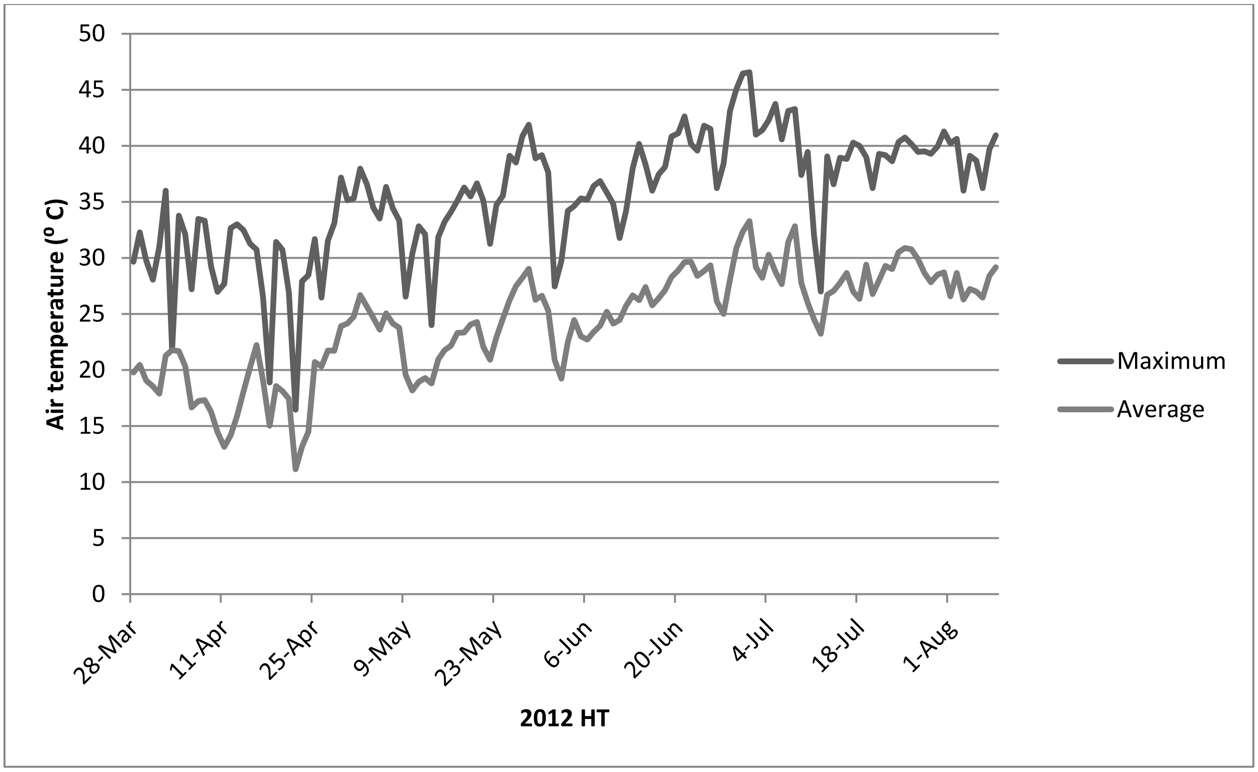
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
2010 OF
Maximum
Average



50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
7-Apr
21-Apr
5-May
19-May
2-Jun
16-Jun
30-Jun
14-Jul
28-Jul
11-Aug
2011 HT
Maximum
Average



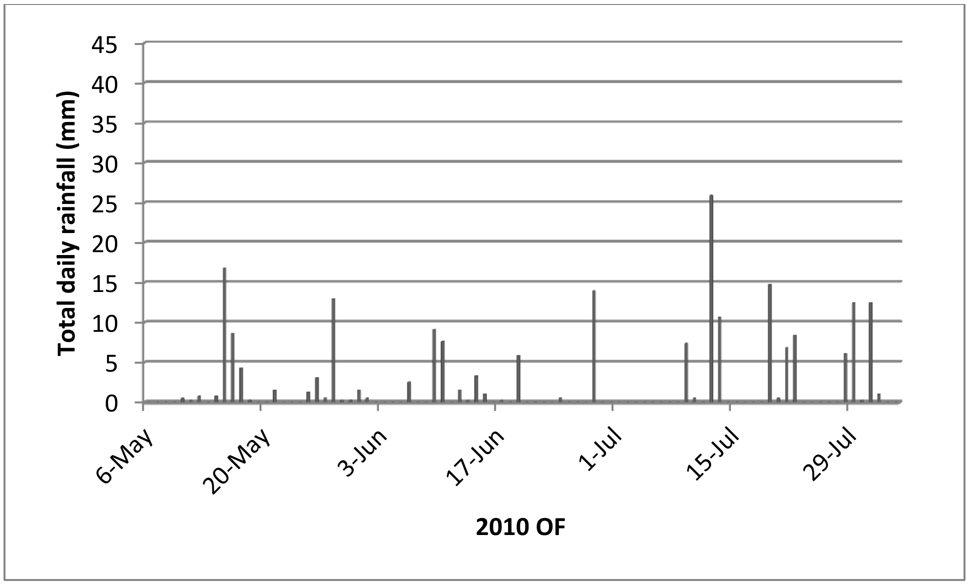
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
12-Aug
2011 OF
Maximum
Average



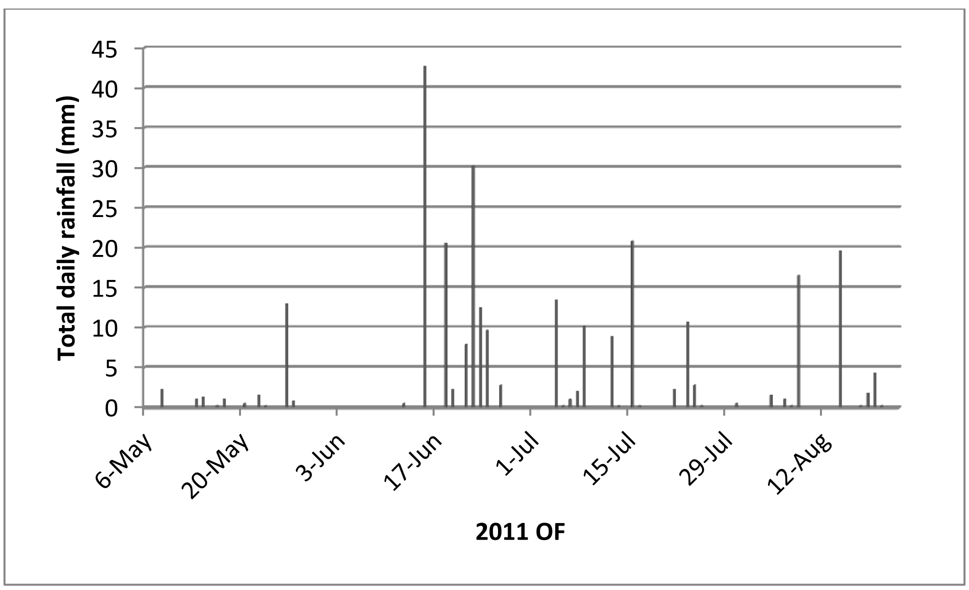
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
28-Mar
11-Apr
25-Apr
9-May
23-May
6-Jun
20-Jun
4-Jul
18-Jul
1-Aug
2012 HT
Maximum
Average

50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
15-May
29-May
12-Jun
26-Jun
10-Jul
24-Jul
7-Aug
2012 OF
Maximum
Average

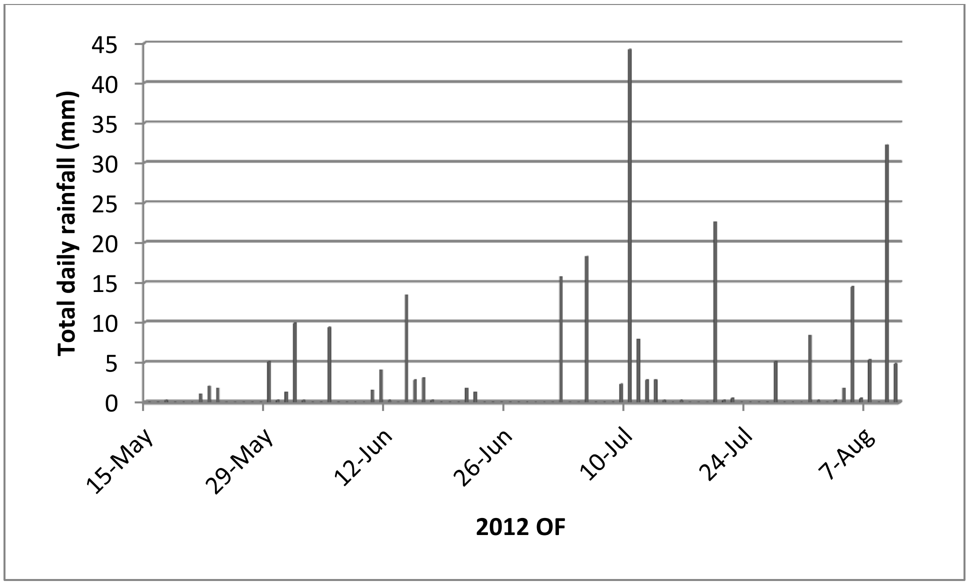
Figure 5. Daily open field (OF) rainfall (mm) amounts for 2010, 2011, and 2012 during the time tomatoes were grown in the open field (OF) plots at the UT ETREC Organic Crops Unit in Knoxville, TN.



45
40
35
30
25
20
15
10
5
0
Total daily rainfall (mm)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
2010 OF



45
40
35
30
25
20
15
10
5
0
Total daily rainfall (mm)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
12-Aug
2011 OF


45
40
35
30
25
20
15
10
5
0
Total daily rainfall (mm)
15-May
29-May
12-Jun
26-Jun
10-Jul
24-Jul
7-Aug
2012 OF

Chapter 3:

Assessment of Degradable Alternatives for Plastic Mulch for Organic Tomato (*Solanum lycopersicum*) Production

Abstract

Degradable mulches were introduced into agricultural production nearly 30 years ago as an alternative to black plastic or polyethylene mulch, with the intention to reduce agricultural plastics in the waste stream. Increased yield and quality are among the many benefits of polyethylene mulch; however, proper disposal of the plastic is time consuming and costly. Degradable mulches reduce removal costs, lessen environmental impacts, and provide functionality during the growing season. Four degradable mulch products, BioAgri, BioTelo, WeedGuardPlus, and an experimental spunbond nonwoven fabric (SB-PLA-10/11/12), were evaluated during 2010, 2011, and 2012 in Knoxville, TN. These four products were compared with black plastic mulch and a bare ground (no mulch) control with respect to tomato (*Solanum lycopersicum*) yield, weed control, and degradability in high tunnel and open field production systems. Marketable tomato yield was greater in the high tunnels than the open field in all three years. Marketable yields in degradable mulch plots were comparable to those from the black plastic plots. Weed growth was minimal in both production systems in all three years except under SB-PLA-10 in 2010. The SB-PLA was reformulated in subsequent years and effectively suppressed weed growth, though showed no sign of visual degradation during the production season. The three commercially available products, BioAgri, BioTelo, and WeedGuardPlus, achieved visual degradation in the open field but WeedGuardPlus did not degrade in the high tunnel. More degradation likely occurred in the open field due to exposure to more environmental stresses (wind, rain, and greater solar radiation).

Introduction

Plastic used as soil mulch in agriculture reduces weed growth, irrigation requirements, soilborne plant diseases, and nutrient leaching. However, it was estimated in 2000 that annual world consumption of soil mulching plastic amounts to more than 725,748 tonnes (Jouet, 2001). Once removed from the field, plastic disposal and recycling can be expensive (Scarascia-Mugnozza *et al.*,

2006) and some growers resort to burning plastic, which is harmful to the environment (Picuno and Scarascia-Mugnozza, 1994). Although plastics have been used in agriculture since the 1950s, degradable plastics were not introduced until the 1980s with the intention of reducing agricultural plastics in the waste stream (Vert *et al.*, 1992).

Degradable mulches have become more available since the mid-90s but tend to be significantly more expensive than plastic mulch (Lawton *et al*., 1999). Degradable mulches have the ability to reduce costs associated with removal and alleviate environmental impacts if incorporated into the soil after use (Anderson *et al.*, 1995). Once incorporated into the soil, degradation occurs allowing the material to be broken-down by microorganisms (Gross and Kalra, 2002; Vert *et al*., 2002; Feuilloley *et al*., 2005). Integrating degradable mulches into the field via tillage is much less laborious than having to remove and dispose of plastic mulches. Mulch incorporation would reduce the amount of labor needed for plastic removal, reduce time and transport costs, and reduce fees associated with properly disposing of the plastic in a land fill (Chandra and Rustgi, 1998).

Many attempts have been made to develop degradable mulches that breakdown in the field once the crop is harvested. Several alternative mulch films are available for use in agriculture to replace non-degradable plastic including paper, starch-based, and spunbond polylactic acid materials. Paper mulch films are completely degradable and once a small crack or tear occurs on the surface rapid degradation results and large cracks ensue (Hutchins, 1933; Anderson *et al*., 1995; Schonbeck and Evanylo, 1998). Paper mulches decompose in the soil once incorporated at the end of the cropping season (Brault *et al*., 2002). While paper mulches have been proven to completely decompose in the soil, they may degrade too quickly (Brault *et al*., 2002). Furthermore, the heavy weight of paper mulch and its habit to easily tear when laid with mechanical mulch laying equipment have limited widespread use (Sorkin, 2006).

In contrast to paper, starch-based polymers do not degrade as effectively as paper and are currently expensive for agricultural use (Halley *et al*., 2001; Olsen and Gounder, 2001; Feuilloley *et al*., 2005).

Starch-based mulches resemble polyethylene mulches regarding appearance and handling performance (Miles *et al.*, 2012) and are easily laid with mechanical mulch laying equipment. However, Greer and Dole (2003) found a combination of starch and degradable plastic can increase degradability too much. Though, Feuilloley *et al.* (2005) found micro-fragments from degradable polymers of currently available degradable mulches to remain in the soil for multiple seasons thereafter.

A spunbond polylactic acid experimental material has recently been developed and may also be an alternative to polyethylene mulches (Wadsworth *et al.*, 2009). This type of mulch is extremely durable and has been found to degrade to a fine powder in the lab. Degradation occurred after five weeks of incubation at 30 ^{o}C when combined with compost (Hakkarainen *et al.*, 2000). However, field studies have not been conducted to determine its degradation during crop production.

Regardless of mulch type, degradable mulches must provide functionality during the growing season when exposed to the environment but must degrade in a timely manner once incorporated into the soil to be commercially viable. Many factors contribute to degradation of mulch films. Ennis (1987) found photodegradable plastic to be differentially broken down depending on the crop grown, the light received during the growing season from the sunlight/temperature interaction, and the production system (Greer and Dole, 2003). Degradation slows under crops like tomatoes that cover more of the exposed mulch as light penetration is reduced, resulting in less UV light reaching the mulch (Csizinszky *et al*., 1995; Graham *et al*., 1995; Scott *et al*., 1989). The growing season influences the rate of the breakdown process and different parts of the world receive different levels of solar radiation from year to year. A region receiving low solar radiation will have slower degradation than a region receiving higher solar radiation (Greer and Dole, 2003). Regarding production systems, high tunnels can further reduce the amount of solar radiation received by the mulch and plants. High tunnels increase air temperature, but they also decrease the amount of wind and exclude rainfall that the mulches would otherwise receive in the open field. Open field production systems are subject to harsher environmental conditions, with unfiltered sunlight and solar radiation, wind events, and overhead rainfall.

This study compares three mulches commercially advertised as biodegradable (one cellulose-based and two starch-based) and one experimental spunbond polylactic acid-based mulch to black plastic mulch and a bareground control. The mulches were evaluated for their effect on tomato (*Solanum lycopersicum*) yield, ability to control weeds, and rates of visual degradation in both high tunnel and open field production systems.

Materials and Methods

This study was conducted in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN and was managed organically. The climate is subtropical with a hot and humid summer. The field elevation is 270 m, soil pH is 6.8, percent organic matter averaged 1.3%, and soil type is Dewey silt loam.

The experimental design was a completely randomized split plot with high tunnel (HT) and open field (OF) production systems as main-plots replicated four times. Four HTs (29.3 m long by 9.1 m wide; Golden Pacific Windjammer Series 5000; Golden Pacific Structures, Cincinnati, OH) were erected at the site in spring 2010. The single-layer plastic covering on the HTs was Durafilm Super 4 (AT Films, Inc., Edmonton, Alberta, CA) with 92% optical transmission. The HTs were oriented North to South and located 3.2 m apart West to East. Four corresponding OF sites (29.3 m long by 9.1 m wide) were created to the East of the HTs located 3.4 m apart West to East and were also oriented North to South. Mulch treatments were subplots, and included BioAgri, BioTelo, WeedGuardPlus, black plastic, SB-PLA-10/11/12, and bare ground as a no-mulch control (Table 16). Each sub-plot measured 4.3 m long by 0.6 m wide.

Pre-plant organic fertilizer (Soybean Meal 7.00 total N, 0.40 elemental P, 0.66 elemental K, Foothills Farmers Co-Op, Maryville, TN) was applied to deliver an estimated 33.63 kg per hectare. The sub-plots were rototilled (Kubota Tractor Corporation; model B7510; Torrance, CA), and drip irrigation (T-Tape, low flow, 16 mm diam., 8 mm, 30-cm emitter spacing, San Diego, CA) was laid in a single row in the center of each bed. In the HT and OF plots, the mulches were laid by hand onto flat, pre-shaped beds on dates listed in Table 17. Mulches were laid by forming furrows at the edge of the bed with the mulch sides placed within the furrows. Soil was backfilled by hand to form a tight mulch layer on the bed surface. Transplant holes (10 cm diameter) were made with a WeedGuard Transplanter 0.6 m apart in a single row in each mulched bed with seven holes per sub plot.

Tomato (‘Celebrity’) was used as the test crop and grown in one of the center beds in each HT and OF plot each year. Tomato seedlings (6 to 9 weeks old) were transplanted on dates listed in Table 17. Tomato plants were pruned to one central leader, and staked using a Florida Weave training system (Kelbert *et al*., 1966). In 2010, HT harvests began 22 June and ended 6 Aug (14 total), while the OF harvests began 13 July and ended 3 Aug (7 total). In 2011, HT harvests began 14 June and ended 12 Aug (17 total), while the OF harvests began 21 July and ended 22 Aug (10 total). In 2012, HT harvests began 21 June and ended 2 Aug (13 total), while the OF harvests began 20 July and ended 15 Aug (7 total). Total and marketable fruit number and weight were calculated based on seven plants in each plot, with plot spacing of 1.8 m between beds and 0.6 m in the bed. Percent marketable fruit was calculated by weight.

Tomatoes were harvested at the “pink to red” stages of maturity following USDA maturity standards (7 CFR § 51.1904). Fruit were then sorted into marketable and non-marketable categories. In 2010, multiple disorders were recorded for each unmarketable fruit, but in 2011 and 2012 only the predominant disorder was recorded. Disorders include fruit cracking, yellow shoulder, and blossom end rot. The number of fruit and total weight for each unmarketable category was recorded. The weights for each unmarketable category were divided by the total unmarketable weight to obtain percent unmarketable.

Water was applied via irrigation twice per week at 67 $m^{3}\cdot ha^{-1}$ (25.4 mm per row) per application in 2010 and twice per week at 33.5 $m^{3}\cdot ha^{-1}$ (12.7 mm per row) per application in 2011 and 2012 from transplanting until the end of the growing season, except when rain fell in the OF plots. Irrigation was applied to the OF plots when rainfall was not sufficient, and soil moisture was determined by touch-testing the soil to determine the amount of moisture in the top 7.62 cm of soil.

In 2010, plants were hand fertilized with Schafer's liquid fish fertilizer (2.00 total N, 0.40 elemental P, 0.17 elemental K) (Thomson, IL, U.S.) at 1.12 kg $N\cdot ha^{-1}\cdot day^{-1}$ every 15 days from 14 May to 15 July for a total of five applications. In 2011, plants were fertilized via driptape at 0.45 kg $N\cdot ha^{-1}\cdot day^{-1}$ every 7 to 10 days from 26 Apr to 11 Aug for a total of 15 applications in the HT plots and 13 applications in the OF plots. In 2012, plants were fertilized via driptape at 0.45 kg $N\cdot ha^{-1}\cdot day^{-1}$ every 7 to 10 days from 13 Apr to 8 Aug for a total of 13 applications in the HT plots and eight applications in the OF plots.

Insects and diseases were monitored weekly in the HT and OF plots via direct observation. Three plants were randomly chosen in each sub-plot and monitoring was limited to one minute or less per plant. Pest control products were applied as needed using a single-nozzle hand-held sprayer (SOLO 430-1G; Newport News, VA, U.S.). In 2010, prevention of late blight (*Phytophthora infestans*) was managed with four sprays copper hydroxide (77% a.i. (Champ WG; Albaugh, Inc., Ankeny, IA)) at label rate of 1.98 kg per hectare a.i. on 4, 17 and 30 June, and 14 July. Black cutworms (*Agrotis ipsilon*) were managed with one application of silicon dioxide (77.69% a.i. (Diatomaceous Earth; Safer®, Woodstream Corporation, Lititz, PA)) applied as a light dusting at the base of the plants on 1 Apr in the HT plots and 24 May in the OF plots. In 2011, green peach aphids and potato aphids (*Myzus persicae* and *Macrosiphum euphorbiae*) were managed with one application of potassium salts of fatty acids (49 % a.i. (M-Pede; Gowan Company, Yuma, AZ)) at label rate of 0.03 ml per liter a.i. on 20 Apr, and with two applications pyrethrins (1.4% a.i. (PyGanic Crop Protection EC; McLaughlin Gormley King Company, Minneapolis, MN)) at label rate of 15.68 ml per hectare a.i. on 19 and 27 May. The 19 May application of pyrethrins (1.4% a.i. (PyGanic Crop Protection EC)) was applied at 8x the label rate, 125.44 ml per hectare a.i., and caused chemical burn on tomato. One application copper hydroxide (77% a.i. (Champ WG)) at label rate of 1.98 kg per hectare a.i. on 16 June was applied to prevent the onset of late blight. Damage from the tomato fruitworm (*Helicoverpa zea*), tomato hornworm (*Manduca quinquemaculata*), and true armyworm (*Pseudaletia unipuncta*) were managed with *Bacillus thuringiensis,* subsp. *Kurstaki,* strain ABTS-351 (54% a.i. (Dipel® DF; Valent BioSciences Corporation, Libertyville, IL)) at label rate of 0.60 kg per hectare a.i. on 21 July in the HT plots and 10 Aug in the OF plots. In 2012, damage from the tomato fruitworm, tomato hornworm, and armyworm were managed with *Bacillus thuringiensis,* subsp. *Kurstaki,* strain ABTS-351 (54% a.i. (Dipel® DF)) at label rate of 0.60 kg per hectare a.i. on 11 June in the HT plots and 9 July in the OF plots.

Microclimate data were recorded with a Hobo U30-NRC weather station (Onset Computer, Bourne, MA, U.S.). Air and soil temperatures, percent relative humidity, photosynthetically active radiation (PAR) and average wind speeds were recorded every 15 min from time of transplanting through final harvest. Soil temperature was measured 5 cm from the center plant at a depth of 5 cm in each plot. Due to the high cost of the weather monitoring equipment, only one HT replication and one OF replication were monitored, and were stationed in the second replication in each production system. Minimal variation among HT and OF replications likely existed due to their close proximity. In 2010, environmental data were measured 124 of 141 days the mulch was in place in the HT, and 97 of 99 days the mulch was in place in the OF due to equipment malfunctions. This missing environmental data occurred at the beginning of the 2010 season. In 2011, a severe hailstorm occurred 27 Apr severely damaging all four HT plastic covers. Plant damage was minimal and determined not to affect overall yields. The HT covers were replaced 31 May and 1 June in 2011.

Mulch degradation was evaluated within a designated 1.5 m by 0.6 m bed area in the center of each plot in every replication. The rating season started when degradation began in either production system and concluded when harvests were complete. A new roll of BioTelo was ordered prior to the second year of production due to improper width specifications (2.1 m instead of 1.2 m) the first year, and a new roll of BioAgri was ordered prior to the third year. New rolls were necessary due to the short shelf-life (18 months) of these mulches, which are both corn starch based materials. The experimental SB-PLA was reformulated prior to each year. Carbon black was added to the original 100% poly(lactic acid) (PLA) formulation in 2011 to prevent light from reaching the soil; in 2012, the formulation was changed to 80% PLA and 20% poly(hydroxyalkonoates) (PHA). WeedGuardPlus and black plastic came from the original roll from 2010 for all three years of the project. Percent visual degradation (PVD), where 0% represented completely intact and 100% represented fully deteriorated, was assessed in the plot area twice a month.

Mulch was removed from an area measuring 0.6 m by 1 m at tomato first-flower (one fully open flower on every plant in each main plot) and after final harvest for further degradation analysis (beyond the scope of this thesis). Weeds were identified, counted, and recorded in the soil under the area from which the mulch was removed, including those growing through rips, tears, and holes as well as those found under the mulch.

Statistical analyses. Statistical analyses compared main effects and interactions of mulch (M), production system (PS), and year (Y). Data were analyzed as a completely randomized split-plot design. All data were subjected to analysis of variance (ANOVA) using PROC MIXED (SAS version 9.3; SAS Institute, Cary, NC). Some data required transformation to meet the normality of variance ANOVA assumptions and outliers were removed that interfered with analysis. The Kenward-Rogers (1997) method was used to determine denominator degrees of freedom (DDFM) for F-tests in the analysis. All means were separated using Fisher's Least Significant Difference test ($\alpha = 0.05$).

Results and Discussion

Fruit Yield. In 2010, total yield by number and weight were greater for all mulch treatments, compared to the bare ground control treatment (Table 18). Marketable yield by number (*P=0.0347*) was greater in the black plastic plots than BioAgri, BioTelo, and bare ground plots, though marketable yield by weight did not differ among mulch treatments. Total and marketable yield did not differ among mulch treatments in 2011 (Table 18), while in 2012, total yield by number was greater in bare ground plots (*P=0.0023*) versus SB-PLA-12 and WeedGuardPlus. By weight, the WeedGuardPlus treatment had lower total yields than all other treatments (*P=0.0027*). However, marketable yield did not vary by mulch treatment. The degradable mulches provided similar marketable yields to the standard black plastic mulch across all three years. The interaction of the production system x mulch did not show differences for any yield parameters (data not shown).

The production system *x* year interaction (Table 19) showed differences regarding total yield by weight (*P=0.0084*). Total fruit weight was greater in 2011 OF than all other production system *x* year interactions. Marketable yield was greater for 2011 HT than all other treatments, except 2011 OF for weight. The 2010 and 2012 OF had the lowest marketable yields. The percentage of marketable yield was greatest in 2011 HT, with more than two times and five times the percent marketable of the 2010 and 2012 HT plots, respectively, and nearly three times the percent marketable as the 2011 OF. In both 2010 and 2011, HT marketable yields were greater than the OF yields (910 and 142% or nine times and 1.4 times, respectively); however, in 2012, HT and OF fields percent marketable did not differ. Even though the HTs yielded less total fruit weight, the HTs produced more marketable fruit compared to the OF due to the protected environment demonstrating the positive effect of HT production on fruit quality.

Differences in the growing degree days accumulated partially explain the yield differences by production system. A greater accumulation of growing degree days allows for more plant growth, flower, and fruit development. Growing degree days measured in the HT system were 25, 29, and 49% greater compared to the OF system in 2010, 2011, and 2012, respectively. Although higher mean temperatures increase the rate at which tomato fruit mature, elevated temperatures reduce tomato fruit weight (Adams *et al.*, 2001; Miles *et al.*, 2012). This partially explains why the OF production system had greater total fruit weight, as the HT system consistently was 4 ^{o}C hotter and had a higher mean temperature than the OF.

In 2011 and 2010, HT temperatures were more conducive for fruit development (Fig. 6), but in 2012 HT temperatures were elevated throughout fruit development contributing to less marketable fruit. Peet (2005) found that cultivars drop their blossoms after experiencing four hours of temperature at or above 40 ^{o}C. This temperature extreme occurred in the 2012 HT between 14 June and 8 Aug for a total of 50 hours (Fig. 6). However, in the 2010 and 2011 HTs, 40 ^{o}C was reached only briefly (< 2 hours) and did not cause blossoms to drop.

Low yields in 2010 may be explained due to low soil N content and low soil organic matter as these can be difficult when transitioning to organic production. In our study, yields were low due to the lack of soil organic matter (1.3%) and microbial biomass which can take many years to build in the soil (Rogers and Wszelaki, 2012). Although this study was managed organically, prior to the study the field had been in conventional small grain production for 35 years.

Irrigation management also affects the number, size, and weight of tomato fruit. The HT production system requires water management through drip irrigation, which is supplied directly to the root zone. In 2010, growth cracks in the HT were greater than 50% (Table 20); therefore, HT irrigation was reduced by one half and applied twice per week in 2011 and 2012. By decreasing the irrigation amount, the occurrence of growth cracks in the HT was greatly reduced. Emmons and Scott (1997) have also shown that direct exposure to sunlight can cause tomato fruit to crack. Direct sunlight is reduced in HTs due to the protection of the plastic covering. Moreover, the OF plants did not produce as much foliage to protect the fruit from direct sunlight.

The OF production system produced larger fruit every year but those fruit had a higher percentage of loss due to cracking, thereby lessening the average marketable weight per fruit. Growth cracks contributed to 56-75% of the unmarketable fruit each year in the OF production system (Table 20). The OF system receives overhead rainfall, supplemented with irrigation. As rainfall is not often predictable in timing or volume, this can contribute to more cracking due to excess water in the fruit. Rogers and Wszelaki (2012) found tomatoes in the OF that are vine-ripened are more likely to crack and split due to excessive irrigation.

In addition to cracking, yellow shoulder affected a large portion of unmarketable fruit each year in both production systems, but in 2011 and 2012 caused nearly twice as many percent unmarketable fruit in the HT versus OF system (Table 20). During fruiting, potassium uptake increases and is important regarding pigmentation of tomato fruit (Huett and Dettman, 1988; Hartz *et al.*, 2005). Low potassium levels cause fruit to have high amounts of internal white tissue known as yellow shoulder (Madakadze and Kwaramba, 2004). McIntyre (2004) found soils that undergo intensive cropping cause available potassium to become exhausted in the soil and fields with low organic matter (< 1.5%) were at higher risk of developing yellow shoulder. In this study soil organic matter was low (1.3%) and is a contributing factor to soil fertility through soil organisms. The soil organisms supply available potassium at a steady rate to plant roots (Chen and Avnimelech, 1986). Kuchenbuch *et al.* (1986) found decreasing water content caused a decrease of potassium transport from the soil to the roots. In this study, soil potassium levels were sufficient; however, moisture levels may not have been sufficient in the 2012 HT. Temperatures were elevated in 2012 compared to 2011 and HT irrigation was not increased to account for increased evapotranspiration resulting in drier soils. High temperatures (>33 ^{o}C) have been found to be a contributing factor for yellow shoulder as well (S. Bogash personal communication). High temperatures, low soil organic matter, and inconsistent moisture levels may have contributed to yellow shoulder incidence in both production systems. The HT production system had a higher incidence of yellow shoulder due to its prolonged exposure to higher temperatures (>33 ^{o}C) compared to the OF production system.

A higher incidence of blossom end rot consistently occurred in the HT production system (4.9-29.5%) than the OF (0.0-0.9%) (Table 20). By the third year, nearly 30% of unmarketable fruit in the HT were a result of blossom end rot. A main cause of blossom end rot results from the inability of a plant to uptake water and calcium (Chen and Avnimelech, 1986; Dorais and Papadopoulos, 2001; Hunter *et al*., 2010). The inability to uptake calcium also occurs from uneven levels of available moisture as a result of inconsistent irrigation causing an inconsistent supply of calcium to the roots for uptake (Chen and Avnimelech, 1986). The HTs were irrigated the same in 2011 and 2012, but temperatures were elevated in 2012, which likely increased evapotranspiration and decreased available water to the roots. Irrigation levels were not increased to account for the greater rate of evapotranspiration likely contributing to blossom end rot. Unmarketability due to blossom end rot was minimal in the OF as moisture levels were supplemented with overhead rainfall in addition to irrigation. While reasons for unmarketability varied by production system, the percentage of marketable fruit did not vary by mulch type (data not shown).

Weed Assessment. Weed pressure was minimal throughout the study except for in the 2010 SB-PLA-10 treatment (Table 21). In 2010 only, a significant interaction between production system and mulch at tomato first flower. The SB-PLA-10 had a greater number of weeds than all other treatments, and three times as many weeds in the HT than the OF. A greater number of weeds likely occurred as the HT elevates temperature allowing for increased weed growth compared to the OF. Moreover, the SB-PLA-10 material did not suppress weed germination during the cropping season. This mulch was white and porous allowing sunlight to penetrate through the mulch causing weed seed germination. Subsequent formulations prevented germination, as carbon black was added to the SB-PLA-11 and SB-PLA-12 formulations to reduce light interception.

Weed populations were greater in 2010 and lessened thereafter. The field site was previously planted with cover crops and the natural seeding of cover crops represented the majority of weeds growing under the mulch treatments in 2010. Weeds did not set seed, which lessened weed populations in the following seasons.

Mulch degradation.

In comparing the final PVD rating date across all three production seasons, mulch degradation was greater in the OF compared to the HT (Table 22). Degradation is attributed to overhead rainfall, wind, solar radiation, high temperature, and relative humidity (Miles *et al.*, 2012). Overhead rainfall and wind speed appear to have contributed to the increased PVD in the OF, as these environmental stresses were not experienced in the HT. The OF received a total of 207, 270, and 343 mm of overhead rainfall during the time mulches were in place in 2010, 2011, and 2012, respectively (Table 17). The OF mulches received more than one half of the total rainfall by mid-season and rainfall coincided with increasing levels of degradation in all three years. However, in 2011 and 2012, multiple heavy rain events (>30 mm per event) occurred during the course of the production season, while only one rain event >25 mm occurred in 2010 (Fig. 7). Rain events help to explain the greater degradation in 2011 and 2012 compared to 2010 OF.

Average OF wind speed was 1.9, 1.2, and 1.3 $km \cdot h^{-1}$ in 2010, 2011, and 2012, respectively; however, wind events greater than 20 $km \cdot h^{-1}$ occurred 87, 77, and 92 hours in 2010, 2011, and 2012, respectively. Wind speed was greatly diminished in the HT production system. Wind events blow soil particles and other debris over the mulch causing lesions that develop into larger tears (Miles *et al.*, 2012). Moreover, once torn, wind is able to get under the mulch, lifting it from the soil and causing further tearing.

The OF also received higher amounts of PAR (>200 $\mu mol \cdot m^2 \cdot sec^{-1}$) each year than the HT and may have contributed to higher rates of degradation (Ennis, 1987; Greer and Dole, 2003) (Fig. 8). The HT mulches demonstrated less degradation as the HT plastic cover reduces the amount of PAR and ultraviolet B (medium wave) radiation the mulches received (Rogers and Wszelaki, 2012).

The Southeastern region of the U.S. is characterized as having hot temperatures (>35 ^oC) and high levels of humidity (>70%). High temperatures and relative humidity were the environmental factors in the HT appearing to contribute to degradation (Table 17). Mulches received no overhead rainfall and received less PAR than the OF, but were in place longer in the HT. Both 2010 and 2011 HT had greater PVD than 2012 HT. The 2012 HT production system sustained higher air temperatures yet the amount of irrigation was not increased. Low soil moisture reduces degradation, as there is not a sufficient level of moist soil in contact with the underside of the mulch. Average daily maximum air temperature was greater in the HT by 4 ^oC (Fig. 6) compared to the OF. Air temperature appears to contribute more to degradation than soil temperature as average soil temperature did not differ significantly between production systems and seasons (Table 17). HTs need supplemental, overhead irrigation at the end of the season to increase soil moisture and hasten the degradation of mulches.

PVD data throughout the production season is presented separately by year and for HT and OF due to significant interactions between the production system and mulch type (Fig. 9). In both production systems in 2010 and 2011 , BioAgri, BioTelo, and WeedGuardPlus had greater PVD by the middle of the season than SB-PLA and black plastic, and maintained greater PVD than SB-PLA and black plastic at the end of the season (Fig. 9 a-d), except in the 2010 HT plot. The relatively high PVD of black plastic (control) in 2010 HT was a result of accidental tearing by field workers. From personal observations, irregular stretch marks appeared on BioAgri and BioTelo in the HT production system after exposure to air temperatures above 30 ^oC. Higher air temperature appears to weaken mulches, but without rainfall, degradation does not ensue as readily in the HT production system. In the 2012 HT (Fig. 9e), only

BioTelo had greater PVD by the middle of the season and maintained greater PVD than all other mulches. However, it was at this point that BioTelo passed its 18 month shelf-life which may have contributed to an increase of PVD. Although the 2011 and 2012 HT was irrigated similarly, the temperature in 2012 was much higher as mentioned above (Fig. 6) resulting in drier soil in contact with the mulch, potentially slowing degradation.

In the all three years in the OF, the BioAgri, BioTelo, and WeedGuardPlus mulches began to degrade in late June to mid-July (Fig. 9). Prior to this increase in PVD, a rain event occurred (28 June 2010, 15 mm of rain; on 15 June 2011, 43 mm of rain; on 14 June 2012, 14 mm of rain) (Fig. 7). In the 2012 OF (Fig. 9f), BioAgri and BioTelo had greater PVD by the middle of the season, but WeedGuardPlus achieved greater PVD by the end of the season. Degradation may have occurred due to the three rain events of 44, 32, and 45 mm experienced 10 July, 9 Aug and 14 Aug, respectively (Fig. 7). This indicates that exposure to environmental stresses contributed to weakening all three of these mulches, but the force exerted on the mulches from overhead rain can hasten degradation, especially for WeedGuardPlus.

Wind also contributed to degradation in the OF, as mentioned above, abrading the surfaces of the mulches. As wind and rain events continue, the tears in the mulch increase in size and increase degradation. BioAgri and BioTelo tended to degrade in a longitudinal fashion while WeedGuardPlus degraded at soil-to-mulch contact areas (Fig. 10). WeedGuardPlus degraded more in the OF than the HT, and OF degradation was similar to BioAgri and BioTelo (Table 22). The experimental SB-PLA mulch showed minimal degradation (< 1.5%) in both the HT and OF production systems during a single growing season.

Degradable mulches are considered to be effective if they limit weed growth and do not breakdown prematurely during the growing season. The critical weed free period for tomato is between 28 and 35 days after transplanting (Weaver and Tan, 1983). The commercially available degradable mulches in the OF were less than 50% degraded by mid-season (Fig. 9; b, d, and f). This slow degree of breakdown in the first half of the season allows for soil warming, weed suppression, and moisture conservation. After further breakdown of the mulches in the second half of the season, weed growth remained insignificant. During the latter half of the production season, the tomato plants were able to provide shade and competition against weeds in addition to the mulch.

While SB-PLA did not breakdown in the field, it may be useful for other agricultural purposes, such as mulching applications for multiple cropping seasons, row cover, or ground cover between rows. The SB-PLA-12 suppressed weeds but did not provide sufficient degradation. A formulation with more poly(hydroxyalkanoates) than poly(lactic acid) may degrade more than the current formulation (Table 16) and additional greenhouse studies are underway.

The three commercially available degradable mulches, BioAgri, BioTelo, and WeedGuardPlus, provided weed suppression, while also degrading throughout the production season. The mulch alternatives all performed comparably to black plastic with regard to marketable yield, indicating these mulches would be suitable replacements for black plastic with respect to weed control and crop performance. WeedGuardPlus, BioAgri, and BioTelo achieved greater than 50% degradation in the OF by the end of the season in two out of the three years of the study. WeedGuardPlus breakdown in the HT was less than 10% in all three years, but could be tilled into the soil at the end of the HT season and would likely degrade with adequate soil moisture. Both BioAgri and BioTelo were more variable in their breakdown (10-40%) in the HT production system, but must be removed from the field in certified organic systems.

Currently, BioAgri and BioTelo are not allowed to be incorporated into the soil in the U.S. due to their formulation, which includes non-organically approved additive(s) (USDA, 2012). However, by the end of season, the consistency of BioAgri and BioTelo was so brittle that physical removal was time consuming and difficult, reducing their practical application in the field. More research is needed to better understand the breakdown characteristics of BioAgri and BioTelo and whether or not they fully degrade once incorporated into the soil. WeedGuardPlus retained comparable yields and weed suppression to the current agricultural standard, black plastic, while also achieving field breakdown and adhering to the organic certification standards.

Appendix: Chapter 3

Table 16. Mulches evaluated in HT and OF tomato production in 2010, 2011, and 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN.		
Mulch Product	Company	Mulch Composition
BioAgri® Ag-Film	BioBag; Palm Harbor, FL	Cornstarch and non-disclosed biopolymers; biodegradable and compostable
BioTelo Agri	Dubois Agrinovation; Waterford, ON, CAN	Cornstarch and non-disclosed biopolymers; biodegradable and compostable
WeedGuardPlus®	Sunshine Paper Co. LLC; Aurora, CO	Cellulosic; biodegradable control
Black Plastic, 1.0 mil	Pliant Corp.; Schaumburg, IL	Standard agricultural polyethylene plastic (control)
SB-PLA-10[z]	Saxony Textiles; Germany	Experimental nonwoven spunbond, white, translucent, 100% poly(lactic acid)
SB-PLA-11[y]	Saxony Textiles; Germany	Experimental nonwoven spunbond, black, 100% poly(lactic acid)
SB-PLA-12[x]	Greenbio; Tianjin, China & Saxony Textiles; Germany	Experimental nonwoven spunbond, black, 80% poly(lactic acid) + 20% poly(hydroxyalkanoates)

[z] Experimental mulch used in 2010.
[y] Experimental mulch used in 2011.
[x] Experimental mulch used in 2012.

Table 17. Growing environment characteristics in HT and OF production systems in 2010[z], 2011, and 2012 at the University of Tennessee East TN AgResearch and Education Center Organic Crops Unit in Knoxville, TN

	2010[z]		2011		2012	
	HT	OF	HT	OF	HT	OF
Mulch laying	23 Mar	4 May	6 Apr	6 May	4 Apr	11 May
Tomato planting	26 Mar	5 May	7 Apr	6 May	4 Apr	15 May
Mulch removal	11 Aug	11 Aug	22 Aug	22 Aug	20 Aug	20 Aug
No. days mulch in place	141	99	138	108	138	101
GDD[yv] (base 10 °C)	1973	1581	2204	1707	2242	1509
Ave. daily max. air temp.[v] (°C)	34.2	33.5	34.7	33.2	35.9	32.3
Ave. soil temp at 5 cm depth[v] (°C)						
BioAgri	26.2	27.0	27.1	27.7	27.2	28.3
BioTelo	27.0	26.8	27.7	28.3	28.2	27.9
SB-PLA-10/11/12	26.5	26.6	26.6	27.2	27.3	27.4
WeedGuardPlus	25.7	26.3	26.4	26.5	26.1	26.2
Black Plastic	27.8	27.3	28.5	28.3	29.2	29.0
Bare Ground	26.9	26.7	27.3	26.7	27.9	27.3
PAR[xv] ($\mu mol \cdot m^2 \cdot sec^{-1}$)	627	850	582	783	597	850
Relative humidity[v] (%)	74.1	79.2	72.5	79.1	70.9	79.7
Total rainfall[v] (mm)	0	207	0	270	0	343

[z] In 2010, data collected in the HT from 9 Apr. until 11 Aug. due to sensor malfunction, and 6 May until 11 Aug. in the OF.
[y] Growing degree days calculated base 10° C as [(Tmax+Tmin/2)-10], with negative daily degree days converted to zero.
[x] PAR is photosynthetically active radiation ($\mu mol \cdot m^2 \cdot sec^{-1}$) for the period of time mulch was in place.
[w] Wind speed measured above the tomato canopy: 150 cm above soil surface
[v] GDD, average daily maximum air temperature, average soil temperature, PAR, relative humidity, and total rainfall were based on the period of time mulches were in place.

Table 18. Total and marketable yield (number of fruit (plot-1) and weight (kg plot-1)) associated with tomato mulch type in Knoxville, TN in 2010[z], 2011, and 2012.

Mulch	Total yield (no./plot)	Total yield (kg/plot)	Marketable yield (no./plot)	Marketable yield (kg/plot)	% Marketable yield (kg/plot)	Average marketable weight per fruit (kg)
2010[z]						
BioAgri	155.3 a	30.42 a	9.3 b	1.95	5.9	0.17
BioTelo	148.9 a	29.53 a	10.1 b	1.90	6.3	0.19
SB-PLA-10	156.4 a	30.72 a	18.4 ab	3.16	10.0	0.15
WeedGuardPlus	152.6 a	31.45 a	15.8 ab	2.99	8.6	0.13
Black Plastic	167.3 a	32.46 a	23.1 a	4.39	13.1	0.19
Bare ground	116.0 b	23.40 b	8.8 b	1.79	7.0	0.11
P value	*0.0397*	*0.0449*	*0.0347*	*0.1446*	*0.3470*	*0.3769*
$LSD_{(0.05)}$	*30.9*	*5.78*	10.1	2.19	7.3	0.09
2011						
BioAgri	165.7	30.1	59.5	10.44	38.6	0.19
BioTelo	162.6	28.5	56.5	9.88	37.6	0.19
SB-PLA-11	177.2	34.0	69.0	12.88	40.2	0.20
WeedGuardPlus	167.7	31.1	62.6	11.35	39.2	0.19
Black Plastic	154.5	28.1	50.9	9.05	36.1	0.19
Bare ground	158.5	27.5	61.1	10.23	40.9	0.19
P value	*0.5535*	*0.1275*	*0.3801*	*0.3257*	*0.6815*	*0.8241*
$LSD_{(0.05)}$	*25.4*	*5.15*	16.7	3.47	6.3	0.02
2012						
BioAgri	148.1 ab	30.46 a	9.4	2.26	6.6	0.26
BioTelo	138.8 ab	26.75 a	9.8	2.20	7.2	0.25
SB-PLA-12	136.1 b	28.26 a	8.6	2.29	6.6	0.18
WeedGuardPlus	115.3 c	20.92 b	11.4	3.09	8.8	0.24
Black Plastic	148.0 ab	31.93 a	9.1	2.41	7.6	0.29
Bare ground	155.1 a	30.91 a	7.4	1.56	6.4	0.20
P value	*0.0023*	*0.0027*	*0.5011*	*0.6835*	*0.8921*	*0.3702*
$LSD_{(0.05)}$	*18.6*	*5.43*	4.0	1.79	4.5	0.11

[z] Total fruit number and total weight of fruit were calculated based on seven plants in each plot, with plot spacing of 1.8 m between beds and 0.6 m in the bed.
[y] Means within a column followed by the same letter are not significantly different ($P > 0.05$) as determined by Fisher's protected least significant difference (LSD) test.

Table 19. Influence of production system (HT and OF), year, and production system x year interaction on tomato yield per plot (4.3 m x 0.6 m) at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

	Total yield (no./plot)	Total yield (kg/plot)	Marketable yield (no./plot)	Marketable yield (kg/plot)	% Marketable yield (kg/plot)	Average marketable weight per fruit (kg)
Production system						
High tunnel	166.2 a[Z]	26.84 b	31.1 a	5.67 a	19.4 a	0.20
Open field	137.9 b	32.58 a	6.8 b	1.62 b	5.9 b	0.20
P value	*0.0388*	*0.0272*	*<.0001*	*0.0015*	*<.0001*	*0.7914*
$LSD_{(0.05)}$	26.6	5.08	10.5	2.28	6.4	0.03
Year						
2010	145.4 b	27.55 b	9.0 b	1.74 b	4.8 c	0.16 b
2011	168.3 a	33.37 a	56.3 a	11.42 a	27.3 a	0.21 a
2012	142.4 b	28.22 b	6.1 c	1.40 b	9.4 b	0.24 a
P value	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*<.0001*
$LSD_{(0.05)}$	10.7	2.41	4.9	1.08	3.1	0.03
PS x year						
High tunnel						
2010	164.3	24.25 c	32.3 b	5.28 b	20.0 b	0.17
2011	175.3	28.83 b	75.8 a	13.61 a	44.4 a	0.19
2012	158.9	27.44 bc	12.3 c	2.53 c	8.3 c	0.23
Open field						
2010	126.6	30.84 b	2.5 d	0.58 d	1.2 d	0.14
2011	161.3	37.90 a	41.8 b	9.58 ab	16.8 b	0.21
2012	125.9	28.99 b	3.1 d	0.77 d	10.6 c	0.24
P value	*0.0714*	*0.0084*	*<.0001*	0.0007	*<.0001*	*0.1996*
$LSD_{(0.05)}$	23.0	4.83	9.9	2.17	6.1	0.05

[Z] Means within a column followed by the same letter are not significantly different (*P*=0.05) as determined by Fisher's protected least significant difference (LSD) test.
[Y] Marketable yield (no./plot), marketable yield (kg/plot), and % marketable yield (kg/plot) were log_{10} transformed, means presented are backtransformed.

Table 20. Influence of production system (HT and OF) on percentage of unmarketable fruit per plot (4.3 m x 0.6 m) in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

	Growth cracks (%)	Yellow shoulder (%)	Blossom end rot (%)
2010			
High tunnel	53.1 b	43.5[ZY]	8.1 a
Open field	74.8 a	41.5	0.9 b
P value	*0.0052*	*0.7827*	0.0039
$LSD_{(0.05)}$	12.4	16.5	3.8
2011			
High tunnel	24.3 b	30.3 a	4.9 a
Open field	63.7 a	18.0 b	0.1 b
P value	*<.0001*	*0.0001*	*0.0025*
$LSD_{(0.05)}$	*9.3*	*3.4*	2.3
2012			
High tunnel	3.6 b	54.4 a	29.5 a
Open field	56.3 a	27.9 b	0.0 b
P value	*<.0001*	*0.0014*	*0.0006*
$LSD_{(0.05)}$	7.7	11.6	10.9

[Z] Means within a column followed by the same letter are not significantly different (P=0.05) as determined by Fisher's protected least significant difference (LSD) test.
[Y] In 2010, all disorders were recorded for each fruit, accounting for greater than 100%. In subsequent years, the predominant disorder was recorded for each fruit. The top 3 reasons for unmarketability are shown.

Table 21. Total weed number per 0.6 m^2 mulch treatment plot at tomato first flower and final harvest in Knoxville, TN in 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

	2010		2011		2012	
	First flower	Final harvest	First flower	Final harvest	First flower	Final harvest
Mulch						
BioAgri	2.3 b	0.0 b	1.0	1.0	0.0	0.1
BioTelo	2.1 b	0.0 b	1.3	0.1	0.0	0.0
SB-PLA	123.7 a	16.0 a	0.1	0.1	0.0	0.1
WeedGuardPlus	1.8 b	0.0 b	0.3	0.0	0.0	0.3
Black Plastic	0.3 b	0.0 b	0.5	0.0	0.1	0.1
P value	*<.0001*	*<.0001*	*0.1492*	*0.4926*	*0.4269*	*0.6816*
$LSD_{(0.05)}$	15.7	1.9	1.0	1.3	0.2	0.3
PS x mulch						
High tunnel						
BioAgri	1.3 cd	0.0	2.0	0.0	0.0	0.3
BioTelo	0.6 cd	0.0	2.5	0.0	0.0	0.0
SB-PLA	204.7 a	17.0	0.3	0.0	0.0	0.0
WeedGuardPlus	0.3 cd	0.0	0.5	0.0	0.0	0.0
Black Plastic	0.0 d	0.0	1.0	0.0	0.3	0.3
Open field						
BioAgri	3.5 c	0.0	0.0	2.0	0.0	0.0
BioTelo	4.4 c	0.0	0.0	0.3	0.0	0.0
SB-PLA	63.0 b	15.0	0.0	0.0	0.0	0.3
WeedGuardPlus	4.5 c	0.0	0.0	0.0	0.0	0.5
Black Plastic	1.3 cd	0.0	0.0	0.0	0.0	0.0
P value	*<.0001*	*0.7632*	*0.1492*	*0.4926*	*0.4269*	*0.1260*
$LSD_{(0.05)}$	1.7	2.7	1.5	1.9	0.2	0.5

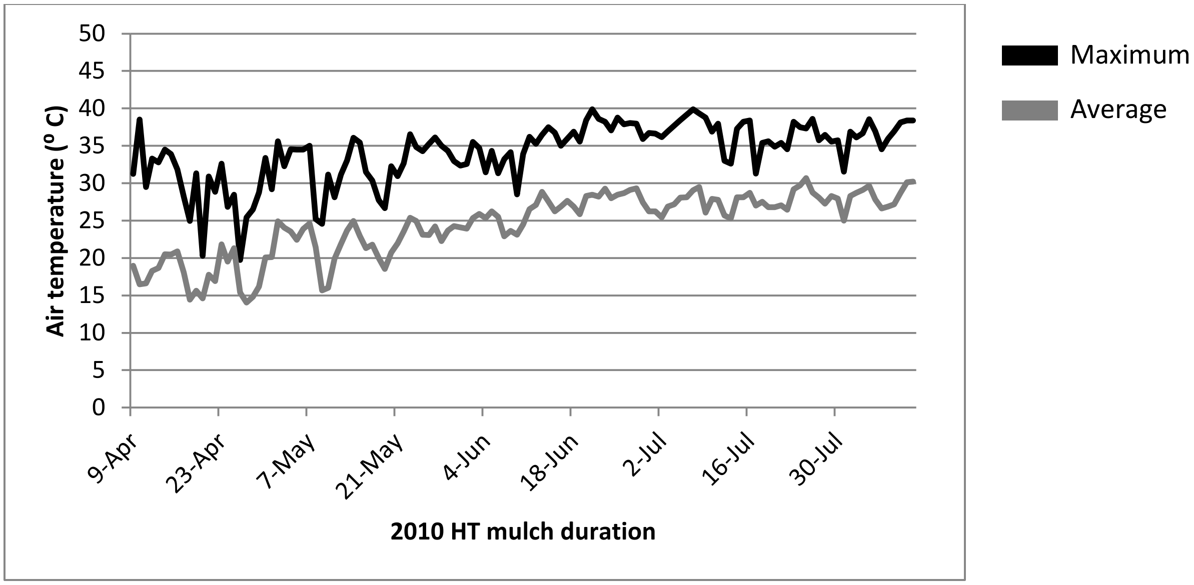
[z] Weed number data at first flower were square root transformed for analysis and means separation; means presented are back transformed.
[y] Means within a column followed by the same letter are not significantly different ($P > 0.05$) as determined by Fisher's protected least significant difference (LSD) test.

Table 22. Influence of production system, production system x year interaction, and production system x mulch interaction on PVD in HT and OF systems for the last rating date per rating area (1.5 m x 0.6 m) planted at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN.

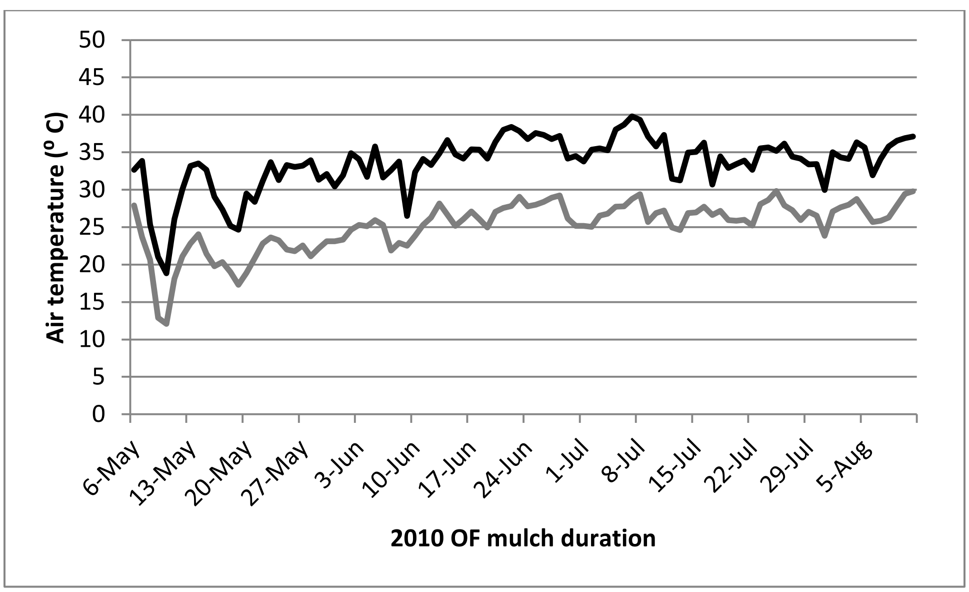
	PVD
Production system	
High tunnel	13.7 b
Open field	32.0 a
P value	*<.0001*
$LSD_{(0.05)}$	6.7
PS x year	
High tunnel	
2010	12.4 bc
2011	20.5 b
2012	8.3 c
Open field	
2010	18.6 bc
2011	39.3 a
2012	38.0 a
P value	*0.0168*
$LSD_{(0.05)}$	11.3
PS x mulch	
High tunnel	
BioAgri	21.8 c
BioTelo	30.7 c
SB-PLA	1.3 d
WeedGuardPlus	7.4 d
Black Plastic	7.3 d
Open field	
BioAgri	47.1 b
BioTelo	47.3 b
SB-PLA	1.0 d
WeedGuardPlus	63.2 a
Black Plastic	1.2 d
P value	<.0001
$LSD_{(0.05)}$	12.2

[y]Means within a column followed by the same letter are not significantly different (P=0.05) as determined by Fisher's protected least significant difference (LSD) test.

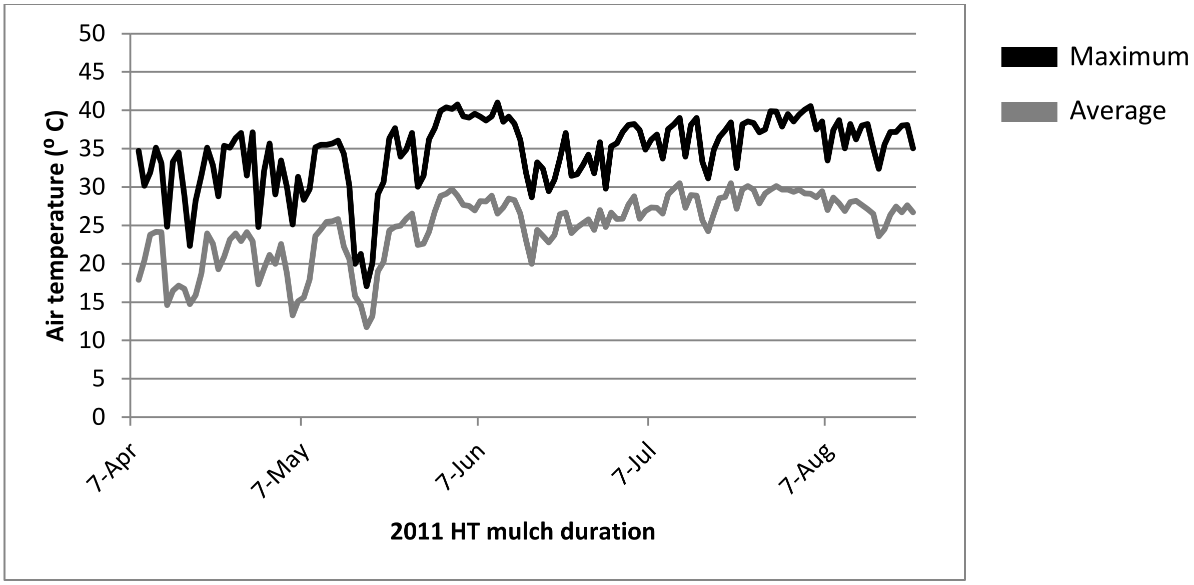
Figure 6. Daily maximum and average air temperature (^{o} C) for 2010, 2011, and 2012 during the time mulches were in place in the high tunnel (HT) and the open field (OF) plots at the UT ETREC Organic Crops Unit in Knoxville, TN.

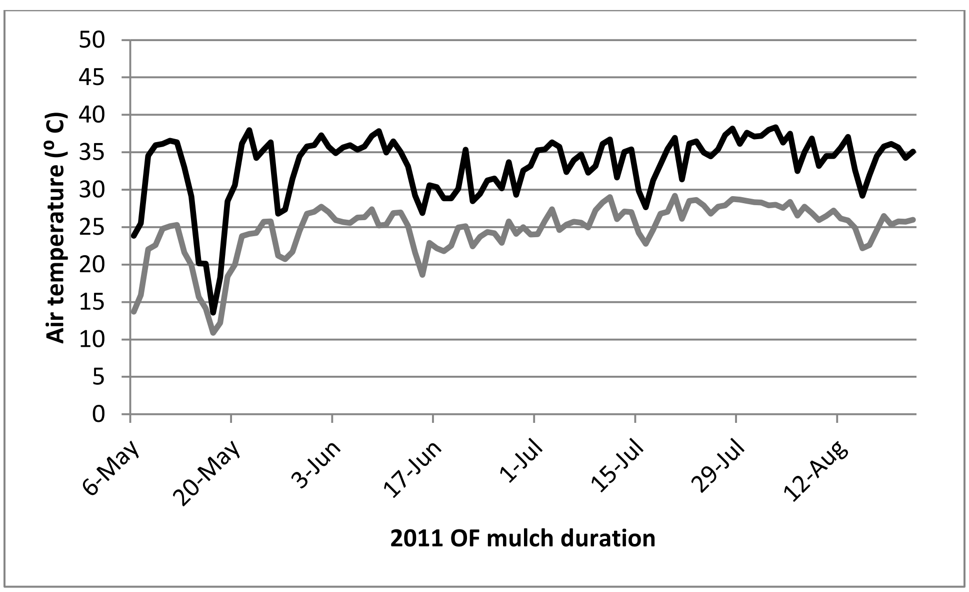


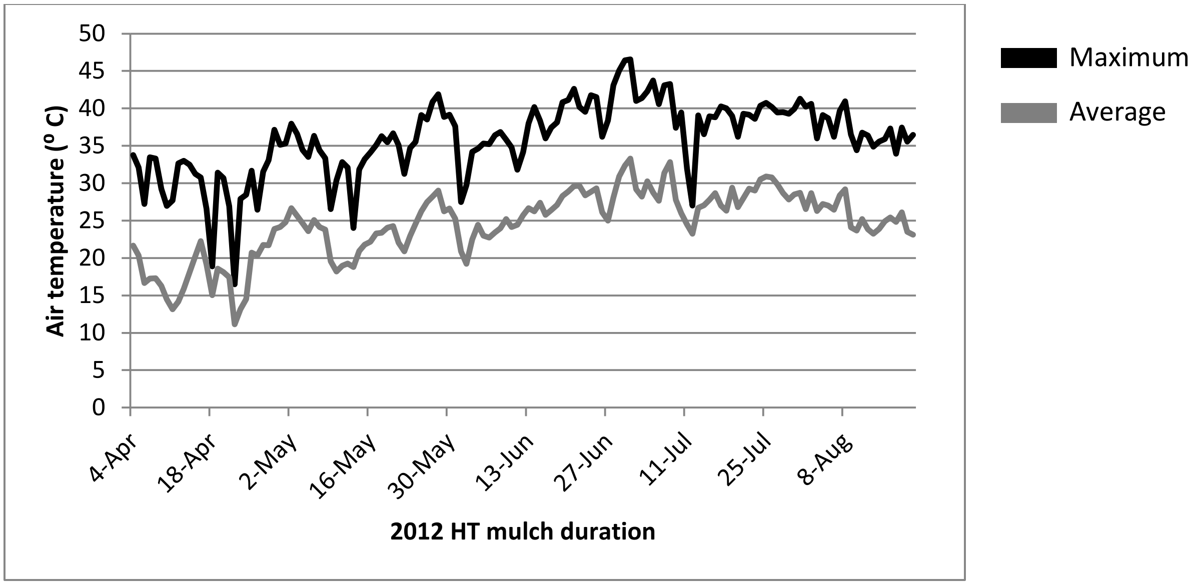
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
9-Apr
23-Apr
7-May
21-May
4-Jun
18-Jun
2-Jul
16-Jul
30-Jul
2010 HT mulch duration
Maximum
Average



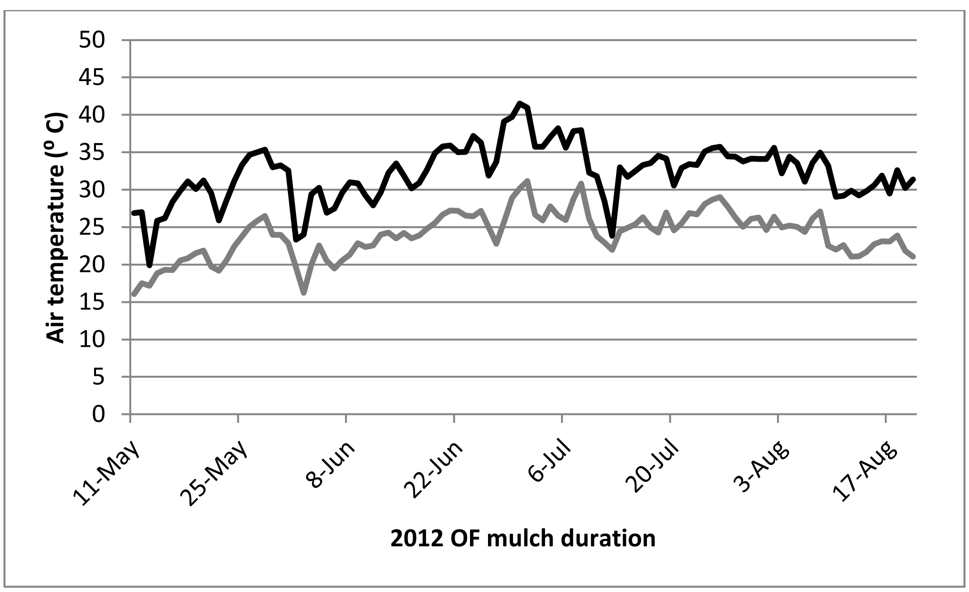
50
45
40
35
30
25
20
15
10
5
0
Air temperature (º C)
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
2010 OF mulch duration


Maximum
Average
Air temperature (º C)
50
45
40
35
30
25
20
15
10
5
0
7-Apr
7-May
7-Jun
7-Jul
7-Aug
2011 HT mulch duration


Air temperature (º C)
50
45
40
35
30
25
20
15
10
5
0
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
12-Aug
2011 OF mulch duration

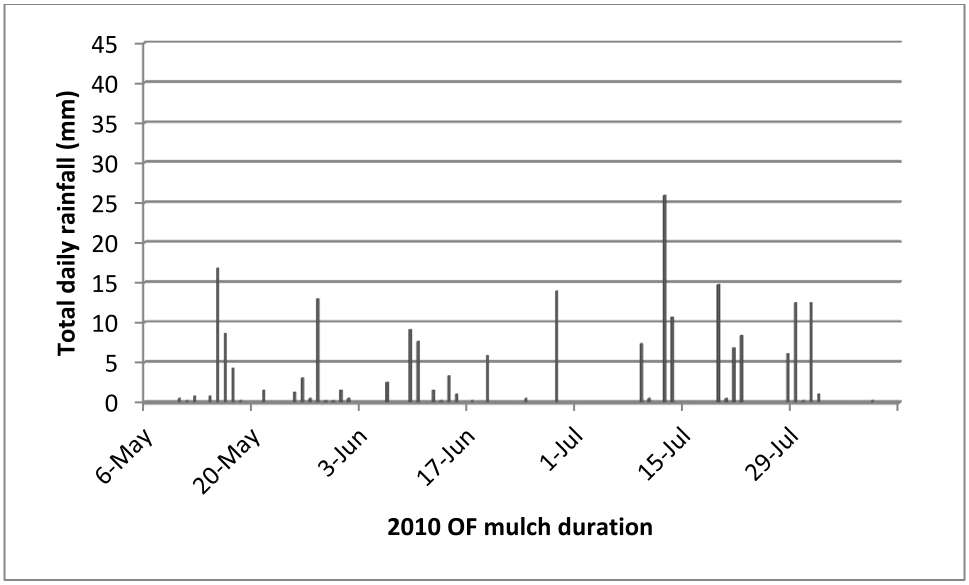


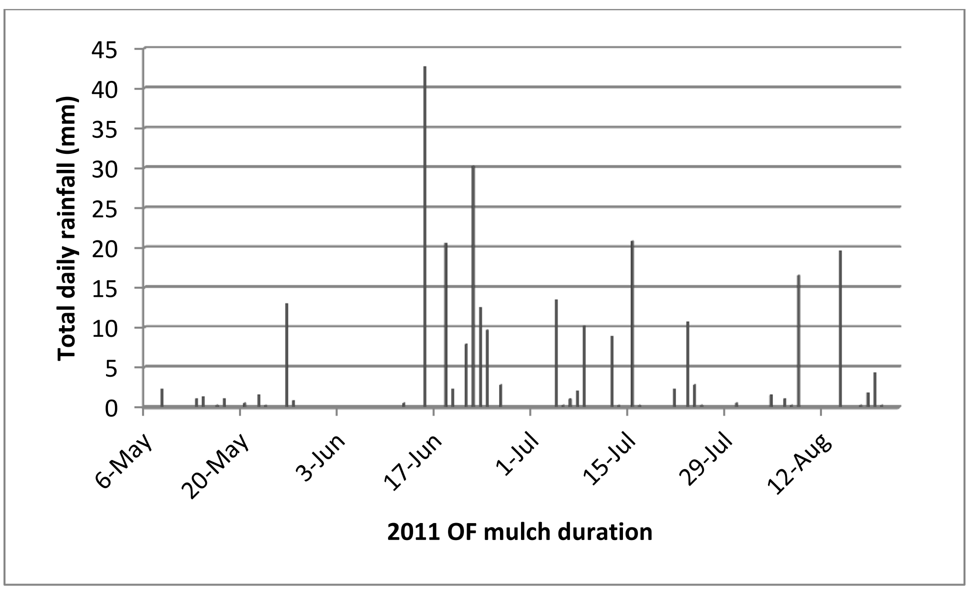
Maximum
Average
Air temperature (º C)
50
45
40
35
30
25
20
15
10
5
0
4-Apr
18-Apr
2-May
16-May
30-May
13-Jun
27-Jun
11-Jul
25-Jul
8-Aug
2012 HT mulch duration

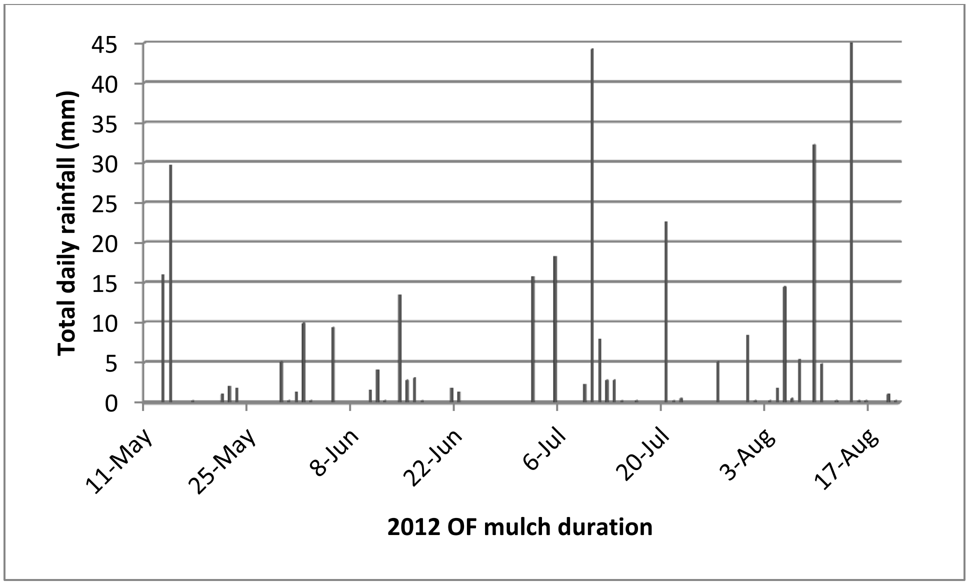


Air temperature (º C)
50
45
40
35
30
25
20
15
10
5
0
11-May
25-May
8-Jun
22-Jun
6-Jul
20-Jul
3-Aug
17-Aug
2012 OF mulch duration

Figure 7. Daily open field (OF) rainfall (mm) amounts for 2010, 2011, and 2012 during the time mulches were in place in the open field (OF) plots at the UT ETREC Organic Crops Unit in Knoxville, TN.

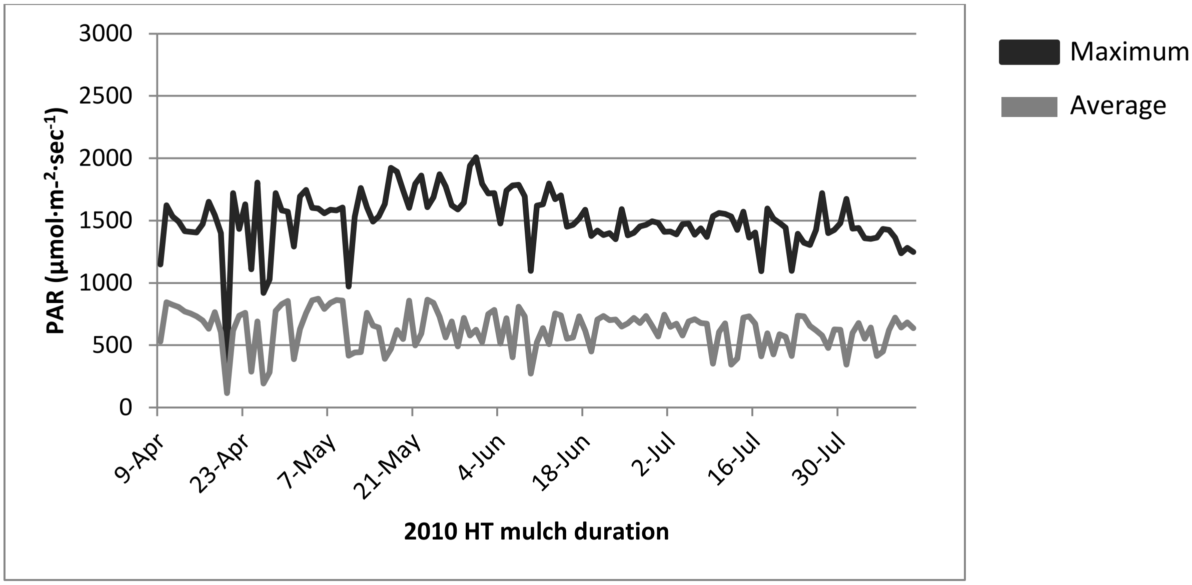

45
40
35
30
25
20
15
10
5
0
Total daily rainfall (mm)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
2010 OF mulch duration


45
40
35
30
25
20
15
10
5
0
Total daily rainfall (mm)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
12-Aug
2011 OF mulch duration

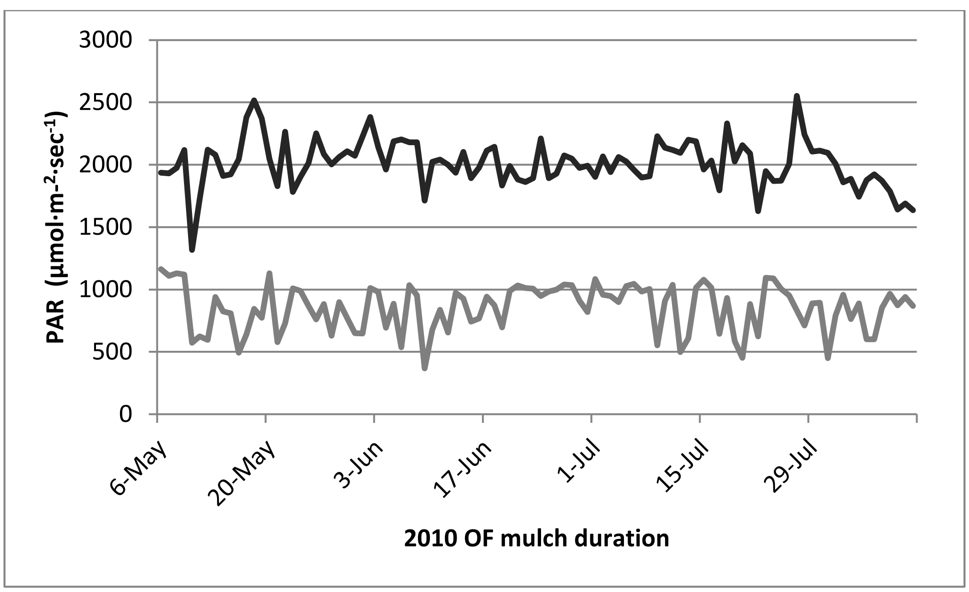


Total daily rainfall (mm)
45
40
35
30
25
20
15
10
5
0
11-May
25-May
8-Jun
22-Jun
6-Jul
20-Jul
3-Aug
17-Aug
2012 OF mulch duration

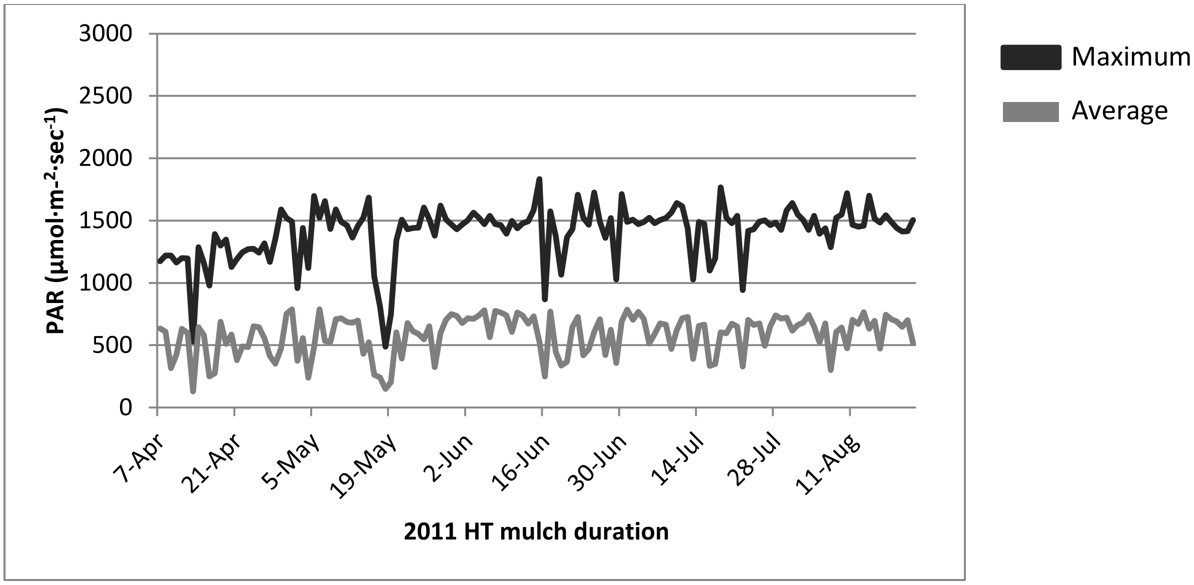
Figure 8. Daily maximum and average Photosynthetically Active Radiation (PAR) (µmol·m^{2}·sec^{-1}) values for 2010, 2011, and 2012 during the time mulches were in place in the high tunnel (HT) and the open field (OF) plots at the UT ETREC Organic Crops Unit in Knoxville, TN.

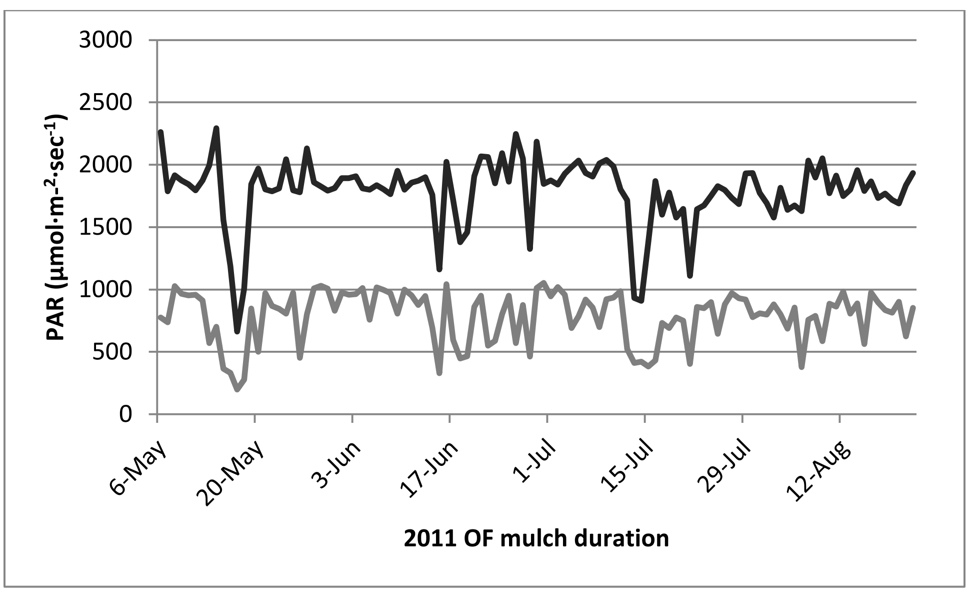


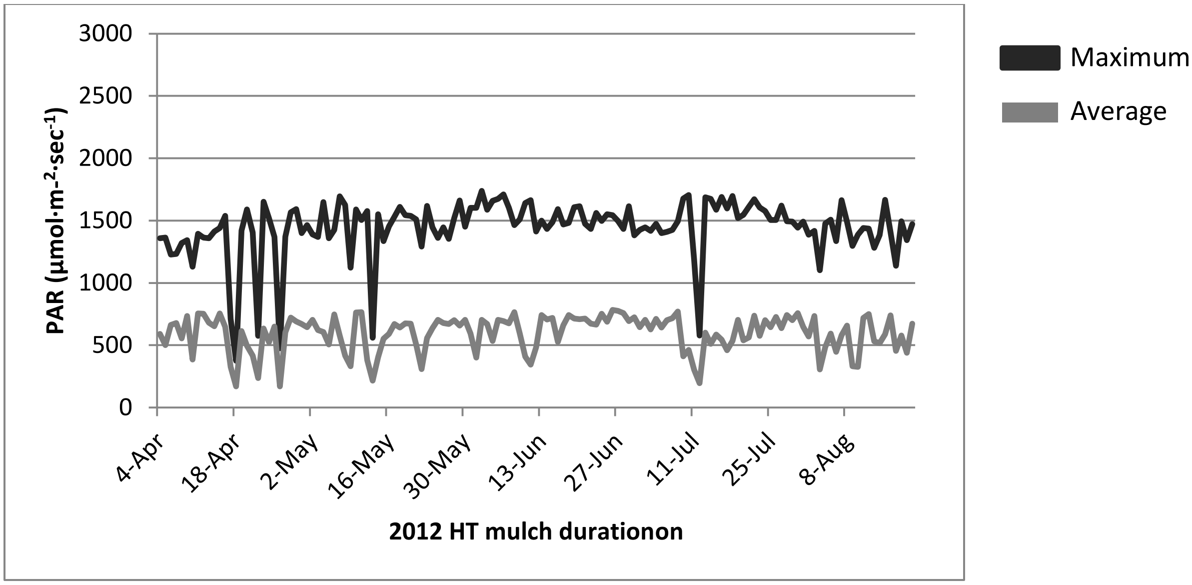
3000
2500
2000
1500
1000
500
0
PAR (µmol·m-2·sec-1)
9-Apr
23-Apr
7-May
21-May
4-Jun
18-Jun
2-Jul
16-Jul
30-Jul
2010 HT mulch duration
Maximum
Average



3000
2500
2000
1500
1000
500
0
PAR (µmol·m-2·sec-1)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
2010 OF mulch duration


3000
2500
2000
1500
1000
500
0
PAR (µmol·m⁻²·sec⁻¹)
7-Apr
21-Apr
5-May
19-May
2-Jun
16-Jun
30-Jun
14-Jul
28-Jul
11-Aug
2011 HT mulch duration
Maximum
Average


3000
2500
2000
1500
1000
500
0
PAR (µmol·m⁻²·sec⁻¹)
6-May
20-May
3-Jun
17-Jun
1-Jul
15-Jul
29-Jul
12-Aug
2011 OF mulch duration


3000
2500
2000
1500
1000
500
0
PAR (µmol·m⁻²·sec⁻¹)
4-Apr
18-Apr
2-May
16-May
30-May
13-Jun
27-Jun
11-Jul
25-Jul
8-Aug
2012 HT mulch durationon
Maximum
Average

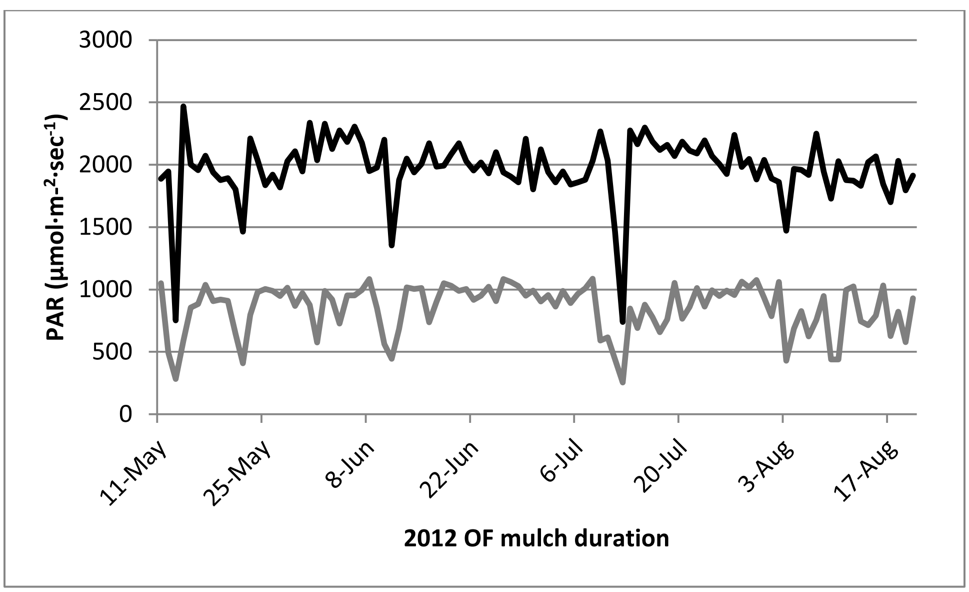
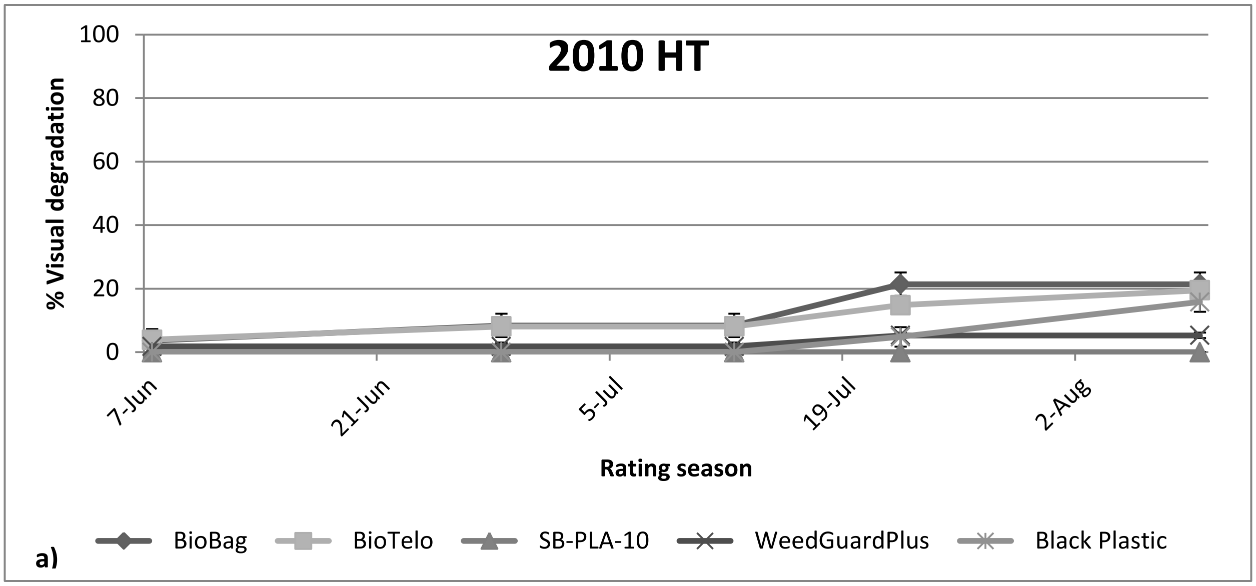
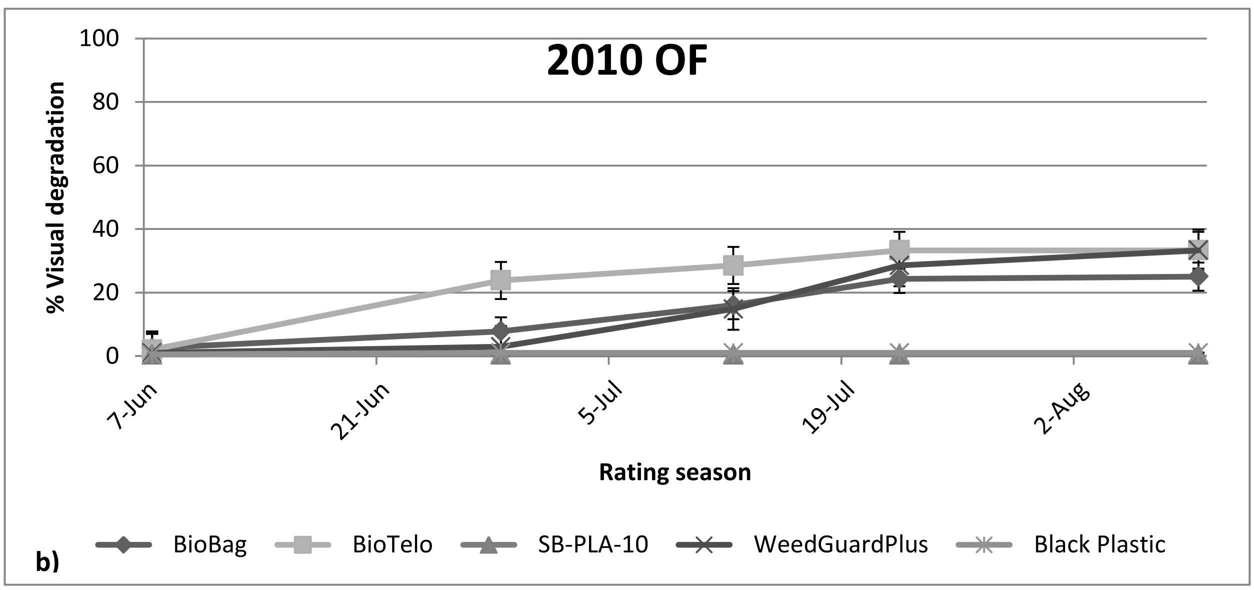
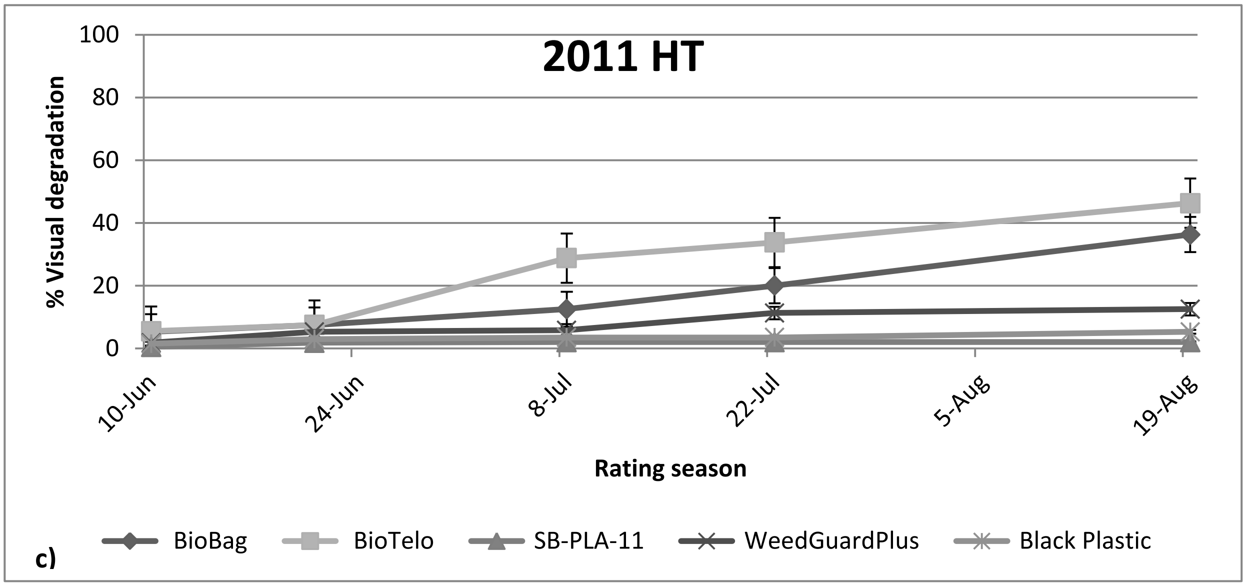
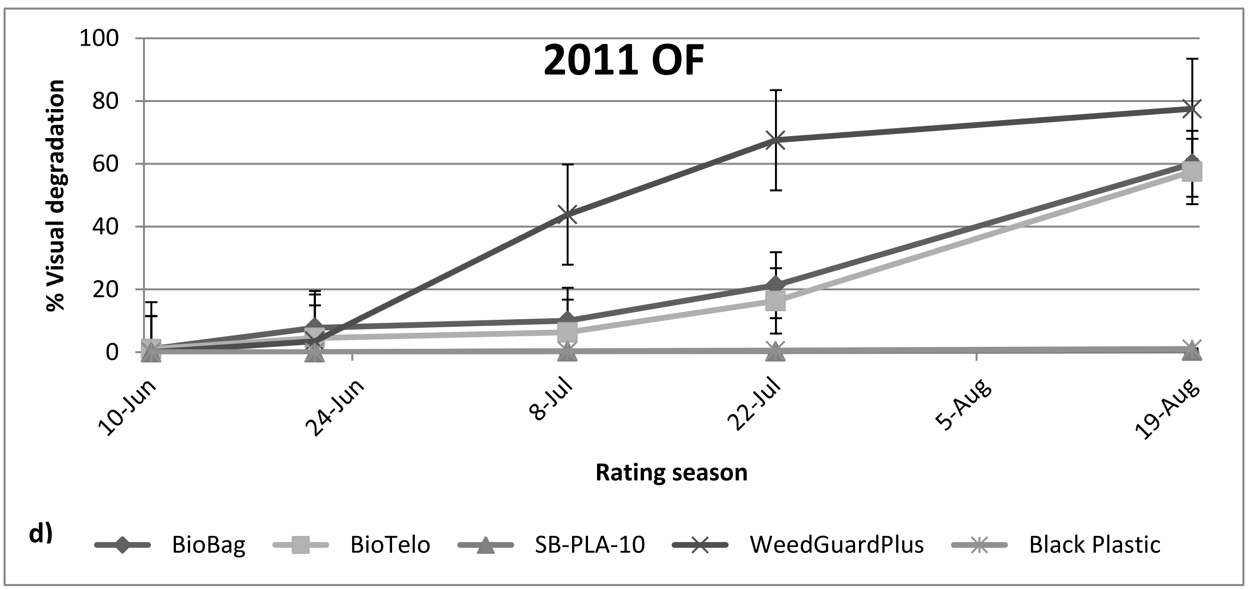

3000
2500
2000
1500
1000
500
0
PAR (µmol·m⁻²·sec⁻¹)
11-May
25-May
8-Jun
22-Jun
6-Jul
20-Jul
3-Aug
17-Aug
2012 OF mulch duration

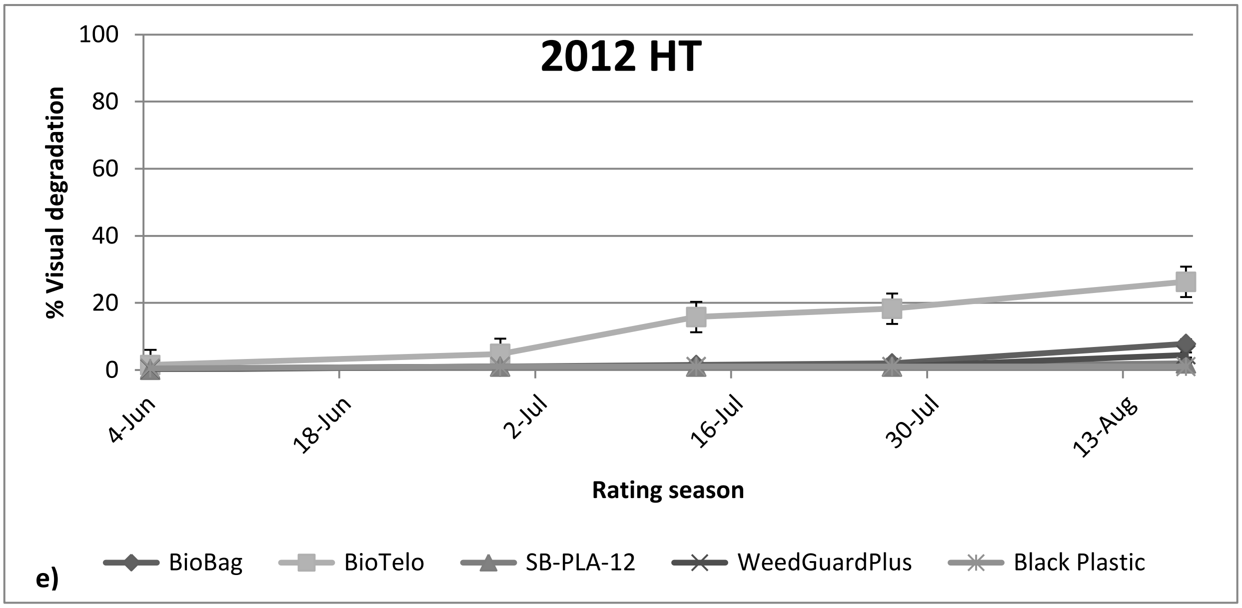
Figure 9. Percent Visual Degradation (PVD) per rating area (1.5 x 0.6m) of mulch treatments in high tunnels (HT) and open field (OF) during 2010, 2011, and 2012 at the University of Tennessee, East Tennessee AgResearch and Education Center Organic Crops Unit in Knoxville, TN. Bars represent the SEM; value ranges for treatments with limited degradation are small and therefore error bars are not evident.


2010 HT
% Visual degradation
100
80
60
40
20
0
7-Jun
21-Jun
5-Jul
19-Jul
2-Aug
Rating season
BioBag
BioTelo
SB-PLA-10
WeedGuardPlus
Black Plastic
a)

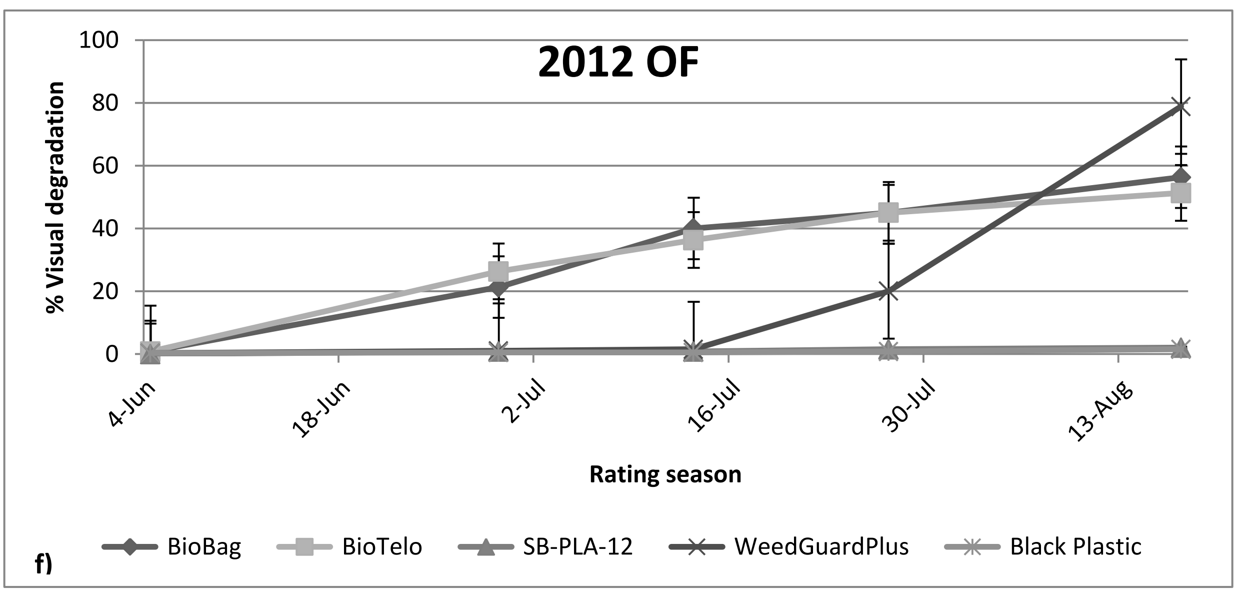

2010 OF
% Visual degradation
100
80
60
40
20
0
7-Jun
21-Jun
5-Jul
19-Jul
2-Aug
Rating season
BioBag
BioTelo
SB-PLA-10
WeedGuardPlus
Black Plastic
b)


2011 HT
% Visual degradation
100
80
60
40
20
0
10-Jun
24-Jun
8-Jul
22-Jul
5-Aug
19-Aug
Rating season
c)
BioBag
BioTelo
SB-PLA-11
WeedGuardPlus
Black Plastic


2011 OF
% Visual degradation
100
80
60
40
20
0
10-Jun
24-Jun
8-Jul
22-Jul
5-Aug
19-Aug
Rating season
d)
BioBag
BioTelo
SB-PLA-10
WeedGuardPlus
Black Plastic



2012 HT
% Visual degradation
100
80
60
40
20
0
4-Jun
18-Jun
2-Jul
16-Jul
30-Jul
13-Aug
Rating season
BioBag
BioTelo
SB-PLA-12
WeedGuardPlus
Black Plastic
e)



2012 OF
% Visual degradation
100
80
60
40
20
0
4-Jun
18-Jun
2-Jul
16-Jul
30-Jul
13-Aug
Rating season
BioBag
BioTelo
SB-PLA-12
WeedGuardPlus
Black Plastic
f)

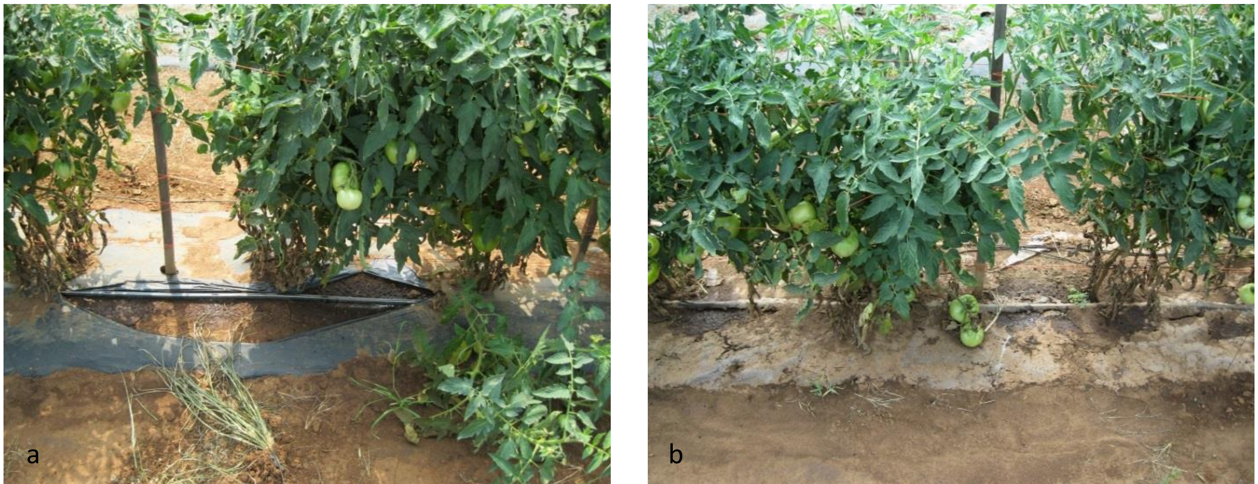


Figure 10. a) BioAgri; OF 22 July 2011; longitudinal tears. B) WeedGuardPlus; OF 22 July 2011: deterioration of mulch in contact with soil.

Conclusions

High tunnels benefit fruit and vegetable production by extending the growing season, increasing yields, and increasing quality. High tunnels are able to extend the season for warm season crops up to one month earlier in the spring and one month later in the fall. Yield and quality are increased in high tunnels due to a longer production season and the exclusion of rain, wind, and severe weather events. High tunnels have been utilized in the Northeast and Midwest for 20 years, but have been underutilized in the hot, humid Southeast.

In this study, organically managed variety trials of six strawberry (*Fragaria* x *ananassa*) and four tomato (*Solanum lycopersicum*) cultivars were evaluated for their performance in high tunnel and open field systems in Knoxville, TN. In addition, specialty crops, such as these, are commonly grown on black plastic mulch to further enhance earliness of harvest, yield and quality. Disposal of the plastic, however, is time consuming, costly and an environmental concern. Degradable mulches reduce removal costs and lessen environmental impacts. Degradable mulch alternatives to black plastic mulch were evaluated in high tunnels and the open field to compare degradability in the production season, weed control, and tomato yield.

Strawberry cultivars were evaluated for differences in yield and quality in the winter of 2011 and spring of 2012 for winter high tunnel, spring high tunnel, and spring open field production systems. The winter high tunnel system produced the largest and highest quality berries but yielded the least due to a short season and heavy insect pressure. Although yields were low, high quality berries produced out of season in winter months can achieve high prices in local markets. The spring high tunnel produced the lowest quality berries and did not achieve yields as great as the spring open field. Unexpected high temperatures in March decreased strawberry fruit quality in the spring high tunnel system as this occurred during fruit ripening. The high tunnel plants received less than one month of rest between winter and spring production which likely exhausted plant carbohydrate storage causing a reduction in flowers produced. The spring open field system produced fruit of good quality and yielded the greatest amount of berries among the three production systems. Temperatures cooled in April, coinciding with flower production and fruit ripening in the open field system. The cultivar Albion yielded the least in both spring systems, but consistently had larger berries, greater firmness, deep red color, high SSC, and high SSC:TA in all three production systems. The cultivar Strawberry Festival yielded the most berries in the winter high tunnel and spring open field systems, and its quality was similar to Albion. The cultivar Chandler yielded the most berries in the spring high tunnel system but had the lowest quality among all cultivars. Careful consideration should be taken when choosing a cultivar based on the production system in which it will be grown to balance yield and quality.

Four tomato cultivars were evaluated in 2010, 2011, and 2012 for differences in yield when grown in high tunnel and open field production systems under organic management. The high tunnel system produced greater total and marketable yields compared to the open field system each year. In 2010, high irrigation levels caused an increase in unmarketable fruit in both production systems. In 2011, both the high tunnel and open field produced more marketable fruit compared to 2010 and 2012. In 2012, elevated temperatures caused drier soils, which limited nutrient uptake causing more unmarketable fruit in both systems. The cultivar Early Girl consistently attained greater yields in both production systems than all other cultivars across all three years, and the high tunnel system more than doubled marketable yields for all cultivars except Red Defender. Cultivars responded differently to the hotter conditions in the high tunnels. Furthermore, the type of market (wholesale or retail) must be considered when choosing a cultivar and production system.

High-value, specialty crops, like strawberry and tomato, are frequently grown on black plastic mulch to prevent weed competition, increase crop quality and yield, and warm the soil earlier in the production season. However, black plastic disposal is time consuming, costly and an environmental problem. Potentially degradable alternatives to black plastic mulch were evaluated in 2010, 2011, and 2012 to determine their effectiveness for weed suppression, for attaining comparable tomato yields, and for degrading in a single production season in high tunnel and open field systems. Three commercially available degradable mulches, BioAgri, BioTelo, and WeedGuardPlus, and one experimental spunbond poly(lactic acid) (SB-PLA) mulch were compared to a black plastic mulch control and bareground (no mulch). All mulches effectively suppressed weeds in both production systems except the formulation of SB-PLA used in 2010. This formulation was white and allowed light to pass through the mulch aiding weed germination. In subsequent years, the color of the mulch was changed from white to black and effectively suppressed weed growth thereafter.

All of the mulch alternatives performed similarly to black plastic and would be a suitable replacement for black plastic regarding weed suppression and yield. The experimental SB-PLA-10/11/12 did not breakdown in either production system, but may be useful for other agricultural applications for multiple cropping seasons as a mulch, ground cover or row cover. BioAgri, BioTelo, and WeedGuardPlus degraded more than 50% in the OF by the end of the season in two of three years. BioAgri and BioTelo degradation was more variable in the high tunnels (10-40%) and WeedGuardPlus was less than 10% in the high tunnel system. However, WeedGuardPlus could be tilled into the soil at the end of the high tunnel season and with adequate moisture would likely degrade, but BioAgri and BioTelo must be removed from the field in certified organic systems. These degradable alternatives could potentially decrease the amount of black plastic mulch in the waste stream, but BioAgri and BioTelo are not currently allowed to be incorporated into the soil in certified organic systems in the U.S. due to unapproved additive(s). Only WeedGuardPlus is currently allowed for incorporation into the field in certified organic systems in the U.S. and was comparable to black plastic regarding weed suppression and yield while achieving sufficient degradability by the end of the production season.

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Appendix

Weed Species

Annual lespedeza (*Lespedeza spp.*)

Broadleaf plantain (*Plantago major*)

Buckwheat (*Fagopyrum esculentum*)

Carpetweed (*Mollugo verticillata*)

Catchweed bedstraw (*Galium aparine*)

Clover (*Trifolium spp*.)

Common bermuda grass (*Cynodon dactylon*)

Common dandelion (*Taraxacum officinale*)

Corn speedwell (*Veronica arvensis*)

Crabgrass (*Digitaria sanguinalis*)

Henbit (*Lamium amplexicaule*)

Johnsongrass (*Sorghum halepense*)

Morning glory (*Ipomoea spp*.)

Pennsylvania smartweed (*Polyganum pennsylvanicum*)

Pigweed (*Amaranthus spp*.)

Prickly sida (*Sida spinosa*)

Prostrate knotweed (*Polyganum arenastrum*)

Prostrate spurge (*Euphorbia maculata*)

Purslane (*Portulaca oleracea*)

Sunflower (*Helianthus annus*)

Vetch (*Vicia spp*.)

Wild buckwheat (*Polygonum convolvulus*)

Wild pansy (*Viola tricolor*)

Yellow foxtail (*Setaria glauca*)

Yellow wood sorrel (*Oxalis stricta*)

Vita

Jeff Martin was born in Chapin, SC, to the parents of Melvin and Becky Martin. He is the last of three siblings: Pam and Susan. He attended Chapin Elementary and continued to Chapin High School in Chapin, SC. After graduation, he attended Clemson University where he was introduced to sustainable agriculture and completed his Bachelors of Science Degree in Horticulture in 2006. After moving to Knoxville, TN and volunteering for two years in AmeriCorps, he accepted a graduate assistantship at the University of Tennessee, Knoxville, in the Plant Sciences Program. Jeff graduated with a Masters of Science degree in Crop Science with a minor in Entomology in May 2013.